Constraint-based Thinking Towards Enhancing Complex Interdisciplinary Designing

Liang, Helen

Award date:
2015

Awarding institution:
University of Bath

Constraint-based Thinking Towards Enhancing Complex Interdisciplinary Designing

submitted by

Helen Liang

for the degree of Doctor of Philosophy

of the

University of Bath

Department of Mechanical Engineering

March 2015

For Grandma, Dad & Ma.

Summary

There are as many perspectives in designing as there have been instances in which it has occured. In each instance, constraints will have invariably arisen in various forms, to the extent that designing and constraints are considered to be an inherently natural pairing. In addition, they are both affected by the challenges of complexity, amongst many others, which is especially compounded by an increasingly significant shift towards interdisciplinary methods and means of working. This has been in response to the influences and implications with regards to the integrated elements of sustainability and sustainable development.

To this effect, the body of research effort presented in this thesis searches for a simpler perspective towards designing, to which constraint-based thinking can be applied. It explores the implications of interdisciplinarity in the context of sustainability and sustainable development. It also considers an example of design-based process within the built environment that is inclusive of multiple disciplines and therefore not only interdisciplinary, but also affected by complexity. In response to these instances of complex interdisciplinary designing, this thesis contributes an exploration of constraint-based thinking and the consideration of an approach which uses design objectives as optimisation constraints, from which a methodology has been created.

Furthermore, this thesis demonstrates constraints as useful in understanding, especially in the context of problem structures and their respective design spaces. As a form of constraint, optimisation objectives are also presented in this thesis as a means of exposing and handling complexity when applied as constrained optimisation for focusing designing efforts. Above all, this thesis advocates the use of constraint-based thinking and simplicity towards enhancing and supporting designing process.

Acknowledgements

This PhD and the research presented in this thesis has been gratefully funded by Arup, and the Engineering and Physical Science Research Council (EPSRC) at the University of Bath.

First and foremost, I would like to give my humble gratitude to my supervisors Prof. Glen Mullineux and Dr. Sally Clift for their encouragement and guidance throughout my post-graduate study and especially at the final hurdle. Also from the University of Bath, I would like to thank those whom I have had the pleasure of working with and whom have invariably supported me on my journey. As part of my collaborations with Arup and engagements further afield, I give special thanks to Jeremy Watson, Joan Ko, David Birch, Neil Grange, and Kerry Mashford for their enthusiasm and contributions towards shaping my research path.

To my many incomporable friends, I am very blessed to have you all and give thanks to Becky Belisle and Timothy Holsgrove of the Daily Constitutional; Jason Bleach, Yuri Donnan, Ellen Grist, and Sarah Ord of Norwood; the Cook and Culley contingent, and the Feldman Family. I would especially like to thank Charlie Gage for the all the cook-ups and hill climbs, Emily Kermode for your incredible kindness and allowing me to fly, Sarah Ryan for your absolute faith and many amazing postcards, Nicole Schlight for the daily facetime even over great waters, Ali Waugh for living through my studies with me, and Carly Whittaker for the many memorable moments at Winchester Road. Också, tack så jätte mycket min bästa skol kompis Robin Long, och tack för att du skickade så mycket bilar till mig. And to Oliver Martin, thank you for all the sundays, sharing your time, and everything else in between.

Lastly, and most importantly, I give my greatest gratitude to my family and my most wonderful parents for their endless support in their very own special way, but also for being the reason that has given me ambition to achieve and my fundamental strength of character.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Design is of great interest with respect to its capabilities and general practice. Much like other similar design-based fields, it is driven by knowledge development, ever-advancing technical capabilities and the pressures of highly competitive business environments. It is also now increasingly common for practitioners of various different disciplinary backgrounds to be brought together in order to work in an interdisciplinary way. This further impacts upon the practice and its consequent developments.

This thesis presents an exploration of general engineering design and the impact of interdisciplinary efforts and influences in which complexity inherently arises. Aiming to provide a supporting approach in response to these matters, existing theory is considered together with constraint-based thinking and how this might advantageously be applied. As a proposal towards enhancing complex interdisciplinary design practice, the background, research question, and objectives are introduced and discussed within the following sections.

1.1 A Simpler Perspective Towards Designing

Artificial products, processes, and systems are in some way or another, all a result of designing. It can therefore be said that design-based thinking and designing as a process has great impact. Depending on the designers, or rather the practitioners and their different disciplinary backgrounds, there are many different perspectives regarding design practice and process (Lawson, 2005). However, it is noted that all who design are fundamentally driven to achieve optimised and/or preferred outcomes (Simon, 1996).

Designing, or design as a specific practice is becoming increasingly complex, this is partly due to demands of interdisciplinary working, and there is much to be said for simplicity. Therefore, this thesis looks towards interpreting design with a simpler perspective by identifying fundamentally common features and similiarties that might support enhancing better designing. It reviews the perspectives of existing design-based fields and assesses various process models of designing, and also considers the closely related elements such as creativity, innovation, and knowledge that are also inherently important (Cox, 2005).

1.2 Constraint-based Thinking Towards Designing

Constraints are some form of restriction or simplification that is either real or artificial. For design-based practices and as part of general decision-based problems, constraints are absolute (O'Sullivan, 2002). They also significantly affect (design) decisions made. With respect to engineering design, constraint-based thinking has contributed to established methods such as constraint resolution using optimisation techniques within modelling environments (Mullineux, 2001 and Hicks et al., 2006). Hence, it is considered that the use of constraints and constraint-based approaches as part of design-problem solving and/or optimisation are complementing.

This thesis explores the constraint-based thinking from which constraint-based techniques have previously been established. It examines the perspectives of constraints with respect to problem solving and the consequences of their interpretation, influence, and interaction. Such thinking is explored with the simpler perspective of design as a form of problem solving in mind, and towards design-problem solving with the aim of enhancing and supporting designing in general.

1.3 Sustainability and Sustainable Development

Within the current climate, designers, governments, institutions, and even the public are responding with increasing vigour to the issues of sustainability. Such issues are also driven by demand of the UK Climate Change Act to reduce greenhouse gas emissions and achieve an 80% reduction against the baseline figures of 1990 (HMSO, 2008). Commonly defined as the combination of elements that are 'people, planet, and profit' (Elkington, 2004), the impact of sustainability has created a shift in designing process making it especially interdisciplinary.

As an emergent discipline, this thesis explores sustainable development as an example of interdisciplinary design and considers the effects of such interdisciplinarity and the general influence upon designing and design-problem solving.

1.4 The Built Environment and Masterplanning

The built environment is a design-based field and profession that is deemed to be 'most multidisciplinary' (Garner & Mann, 2003). It is heavily influenced by the issues of sustainability and significantly contributes to the UK's carbon (CO_2) emissions. Hence, the current vigour and interest towards making general contributions towards it.

This thesis examines the built environment and more specifically the practice of masterplanning which is design-based, and provides an integrated service provision for the design, development and/or regeneration of urban spaces. It brings together practitioners of multiple disciplines and is subject to strict client demands, legislation and statutory requirements. It is therefore an example of highly interdisciplinary work influenced by sustainability and which is also very complex. Hence, it is used as the setting for the research question and objectives of this thesis.

1.5 The Research Question and Objectives

Design has an inherently problem solving nature (Ullman, 1997) that is both complex and multifaceted (Blessing & Chakrabarti, 2009). It has many existing and continuously emergent influences, such as sustainability and sustainable development, that affect its general practice. With respect to design, constraints are important to both the nature and structure of design-problem solving which has an affect towards design thinking. In considering the fundamental nature of both constraints and design, constraint-based thinking is proposed as a potential approach towards managing design that is both complex and interdisciplinary. This thesis answers the following research question.

"Can constraint-based thinking be applied to enhance existing practice of designing and efforts of design thinking in order to support that which is both interdisciplinary and complex?"

In order to answer the research question, this thesis demonstrates the fundamental nature of engineering design as a simple problem solving process that can be specified and solved with the constraints involved. It looks towards the use of general constraint-based thinking in order to enhance design-problem solving and answers the research question through a number of objectives.

1. To critically compare and contrast designing processes and their significant elements to identify common features towards a simpler perspective in designing and design-based thinking (Chapter 2).
2. To explore the use of constraints and constraint-based thinking, their associated approaches, tools, and methods, towards enhancing designing process (Chapter 3).
3. To explore sustainable development as an example of interdisciplinary design and therefore the consequent influence of sustainability upon so-called sustainable design (Chapter 4).
4. To explore the built environment as a design-based field that is an example inherently interdisciplinary, affected by sustainability, and demonstrates complexity (Chapter 5).
5. To propose constraint-based thinking as a means of enhancing complex interdisciplinary designing (Chapter 6).
6. To demonstrate constraint-based thinking enhances existing designing and towards that which is both interdisciplinary and complex, in particular:
   - To demonstrate an interdisciplinary and complex instance of design-based practice to which constraint-based thinking can be applied (Chapter 7).
   - To demonstrate that even the most stringent constraints in the form of legislation and statutory requirements can be a positive stimulus in designing (Chapter 8).
   - To demonstrate how constraint-based thinking can be applied as an instance of interdisciplinary and complex designing, and thus how designing can be translated into a constraint-based methodology (Chapter 9).

- To formulate an approach towards interdisciplinary and complex designing using constraint-based thinking (Chapter 10 and 11).

1.6 Research Scope and Contribution of the Thesis

This thesis provides a simpler perspective towards engineering design that may be enhanced with the use of constraint-based thinking. Particular emphasis is placed on the importance of generating understanding with respect to problem structures, design space or otherwise. It is supported with the contribution of the created extraction and analysis methodology (EAM), and is based on principles of constrained optimisation that supports exposing and handling of complexity and interdisciplinarity. This thesis generally encourages the prescription of constraint-based thinking in enhancing endeavours towards better designing in general.

Chapter 2

Perspectives of Engineering Design and Design Thinking

"Everything around us that is not a simple untouched piece of Nature has been designed by someone" - Nigel Cross.

Design is complex and multifaceted (Blessing & Chakrabarti, 2009) and there exist many different perspectives of what engineering design and design thinking is. This chapter reviews existing theory in engineering design and the closely related elements of creativity, innovation, and knowledge. It critically compares and constrasts models of designing process against phases of problem solving with respect to common features that are identified in order to provide a simpler perspective towards design and design thinking in general.

2.1 Understanding Designing and Design Thinking

It is not easy to explicitly define designing/design. However, there are many different perspectives that are arguably defining in nature and represent some level of understanding. This is important to those who apply design thinking, which this thesis considers to be the specific mindset in choosing to apply designing processes, tools, and techniques. This section firstly considers the scope of engineering design influence, who design thinking is important to, and then begins to explore existing perspectives of what engineering design is.

2.1.1 The Influence and Influences of Engineering Design

As stated by Cross (2000) under the heading of this chapter, 'everything has been designed by someone', which draws attention towards the general breadth of design-based activity. Indeed, engineering design has a wide scope that has great influence and many influences. It is especially motivated and driven by improving everyday life with a strong consideration of not just science, but also of culture.

Figure 2-1 shows engineering design at the centre and intersection of production, art, science, and politics (Penny, 1970 cited by Pahl & Beitz, 1984, p.1). It demonstrates these and others as discrete disciplines or fields that may influence or be influenced by engineering design.

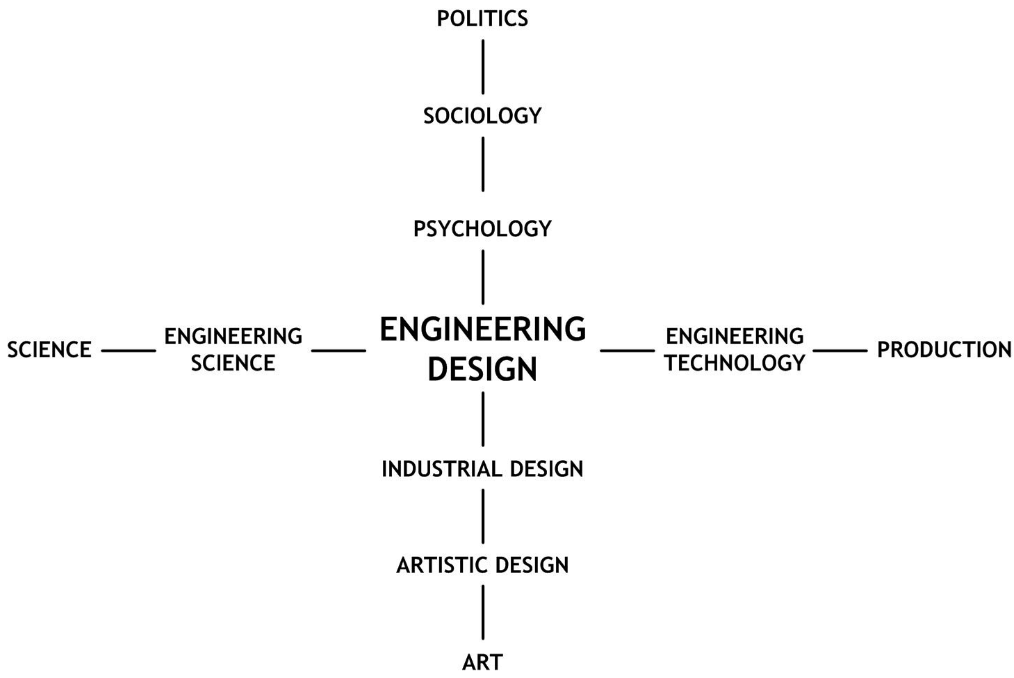

Figure 2-1: Influences of Engineering Design (Penny, 1970 cited by Pahl & Beitz, 1984, p.1).

Engineering design has an influencing role in all things that are man-made, as do the discrete disciplines shown in Figure 2-1 by making their own unique contributions towards engineering design. At the same time, they might equally be affected by design itself. In this way, engineering design also naturally brings together different disciplines and/or fields.

Referring to the disciplines shown in Figure 2-1 and how they might influence each other, ‘engineering science’ and ‘engineering technology’ allows the ‘production’ and manufacture of different artefacts. Yet, the design of these are strictly within the remit of the manufacturing methods available, technical capability, and even business priorities. The mutual consideration of different influences upon each other has even given rise to disciplines such as Design for Manufacture (DFM). Another example where two influences might be brought together is that of ‘art’ in design. This is where the final artefact is not only driven by funtion but also by aesthetic form and would therefore be influenced by disciplines more closely related to ‘industrial design’ or ‘artistic design’. Finally, the human perspective of design with respect to an artefact and its user, but also why design is done the way that it is, and how it might be carried out, is arguably but fundamentally influenced by cognition and social convention. In engineering design, there is a particular affinity towards the elements of creativity, innovation, and knowledge with respect to cognition and culture. As influences these all fall under the disciplines of ‘psychology’, ‘sociology’, and ‘politics’.

At the most basic level, all designing actions are under the influence of principles that extend from ‘science’ and the physical and natural laws such as gravity or Newton’s laws of motion. It is further subject to laws that are set by governments, social policy, and regulating bodies in the form of legislation and statutory requirements.

2.1.2 Design Theorists: Who Design Thinking is Important to

Part of understanding designing is not only in how design might be defined, but also in the knowledge of who design thinking might be important to. For those who experience or are involved in design thinking as part of their practice and/or profession, there lie advantages in having an implicit understanding. They are whom this thesis considers to be 'design theorists' and often contribute their own perspectives of design, which are most likely shaped by their profession (Lawson, 2005), as well as individual experience. In general terms, such theorists may be categorised into groups of different perspectives (Ralph & Wand, 2009) and will have their own motivations regarding their interest towards design thinking. These are the practitioners, the instructors and the researchers of designing.

- **Practitioners -** those who practice designing themselves.
- **Instructors -** those who teach or provide design education.
- **Researchers -** those who perform research in designing.

Understanding designing and design thinking is important to each of these groups as they are also considered to be 'learners'. That is to say that each practitioner, instructor, or researcher has something to learn, no matter what they already know. They are each driven to continuously improve upon what they currently know and how they do it. For example, by learning new design skills, different approaches or new methods. They may even learn from each other. Furthermore, the advantages that follow improvement in design practice further extend to the wider community of those who experience the consequences of designing/design as a client, consumer and/or user of the end product.

2.1.3 Perspectives of What Engineering Design is

The origin of the word design comes from the latin designare; meaning to designate. The Oxford English Dictionary defines design as follows (OED, 2012).

- *noun* A plan or scheme conceived (in the mind) and intended for subsequent execution.
- *verb* To do or plan (something) with a specific purpose in mind.

When considering their literal interpretations, the terms 'designing' and 'design' which are often used interchangeably, are mostly associated with actions such as planning, scheming, and decision making. Whilst this is informative, it indicates little else and all too often describes the end-point of design as artefacts or rather products. In reality, design efforts may produce results with various forms. They may be hand-held products, buildings, and/or structures but they may also take form as some sort of strategy, a specific process or methodology, or even a system arrangement. Furthermore, it is interesting to note that a formally and universally accepted definition of design is yet to be made (Blessing & Chakrabarti, 2009). However, this is not surprising considering the many disciplines and/or fields that are involved. Historically, there have been many attempts to define what engineering design is and even though they offer many different perspectives, they are valuable nonetheless.

In exploring the 'Nature of Design', Cross (2000) describes design as a process of creating a final description (of an artefact). This is interpreted to be a form of a final solution that satisfies a design brief, which in general embodies the 'specific purpose' or rather end-point for the designer. A similar view by Mostow (1985) also considers that the purpose of engineering design is to construct a structure/artefact description. In all such cases, as described by Simon (1996), the focus of all design activity is to reach a 'preferred end-point' by *"changing existing situations into preferred ones"* (Simon, 1996, p.129).

Design has also been interpreted as *"a dialectic between the designer and what is possible"* (Tong, 1984 cited by Mostow, 1985, p.44). Essentially, this means that the designer goes back and forth between what is and is not possible through a repeated exchange of reasoning towards achieving an objective. The notion of design as a form of 'dialectic' is also reflected by Suh (1990) as *"a continuous interplay between what we want to achieve and how we want to achieve it"* (Suh, 1990, p.25). Such perpectives of design describe design as iterative and a non-linear process that pushes a designer's effort back and forth between the design problem and the design solution.

Blumrich (1970) offers the definition that *"design establishes and defines solutions to and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way"* (Blumrich, 1970, p.1). In this, it is evident that there is an emphasis on the perspective that design is a process of solution search and problem solving, which is echoed by sources including Ullman (1997).

To attempt to succinctly define or describe design is a useful exercise in developing understanding. It reveals the elements that make the process of engineering design what it is, even though a universally accepted definition is arguably impossible. Looking towards these elements as the actions that constitute designing process is useful, especially when taking the viewpoint that design can be more explicitly defined by describing 'how it is done'. Engineering design models offer unique perspectives by design theorists: the researchers. They are significant and positive contributions of design research (Mostow, 1985) that are the result of careful inquiry and demonstrate a particular approach or set of specific activties. Often, once established, they are used as part of frameworks to facilitate and support design activity in a structured or systematic way. They are therefore a point of interest in this thesis for critically comparing and contrasting different designing process models.

2.2 Engineering Design and Designing Process Models

Engineering design models are akin to what Kuhn (1962) defines as 'paradigms' in the seminal work, 'The Structure of Scientific Revolutions'. They are established routines that are believed to be a set of definitive actions. Each is a distinct pattern, model or exemplar which essentially provides a framework of good practice. As such, they are a representation of how things should behave or the way in which certain systems should work. This is to the extent that the set of established actions may be reproduced and repeated without failure to do so. However, they are also each considered to be a continuous *"object for further articulation and specification"* (Kuhn, 1962, p.23).

Previous efforts in engineering design have yielded a number of paradigms that are formally emobodied as 'designing process models'. Altogether, they represent a wealth of empirically acquired knowledge. Each model is synonymous with its respective theorists, their background, and disciplinary context. As previously mentioned, it is therefore considered to be a specific perspective and/or unique understanding towards what engineering design is and by how it is done. The knowledge captured and represented by these designing process models offer the design community with a foundation for established patterns of working. They are often central to any descriptions made about designing/design and have truly become the paradigms that much of engineering design research and practice is founded upon. Along with ways of working, these models are indeed continuously investigated. This is in response to the challenges of competitive business environments, continually progressive technology advancements, and the simple desire to improve upon existing design practice and process.

The models of designing process that currently exist do vary in their construction, but they are not necessarily all that dissimilar. There are many shared commonalities or rather key activities that can be identified across different designing models that also contribute to how they might be classified. To begin critically comparing and contrasting different designing process models, the remainder of this section examines an initial selection of significant designing models that are classified as being either 'prescriptive' or 'descriptive' models.

2.2.1 Prescriptive Designing Models

Prescriptive designing models are those that suggest a specific or adopted way of working. Described as *"distillations of best practice"* (Wynn & Clarkson, 2005, p.40), they are generally more algorithmic and systematical in nature (Cross, 2000). The models of Pahl & Beitz (1984), Archer (1984 cited by Cross, 2000) and Archer's three-phase model (1984 cited by Cross, 2000) are examples of prescriptive models. They are discussed here and are most simply, designing models that represent 'how design should be done'.

Pahl and Beitz

The development of a systematic approach towards engineering design originated in Germany in the early 1970s, embodied by the Association of German Engineers. As a collaborative effort, this led to the development of the Verein Deutscher Ingenieure (VDI) 2222 guideline (VDI-Richtline 2222, 1973 cited by Pahl & Beitz, 1984, p.19), which then formed the foundations of the systematic approach captured by Pahl & Beitz (1984).

Originally an attempt to provide a comprehensive theory of engineering design, it is now well known for being one of the most accepted and prominent designing models within the engineering design community. It is represented in Figure 2-2 (p.10) and shows the collection of actions and sub-actions as the steps that make up the overall flow of work. Looking towards the right of the figure, it can be seen that there are four abstracted phases which in general, are most commonly used to describe the designing process. These named phases are 'clarification of task', 'conceptual design', 'embodiment design' and 'detail design'. They have become significantly synonymous with other designing models and often appear under various names, in other models, that describe the same and/or similar phases of designing.

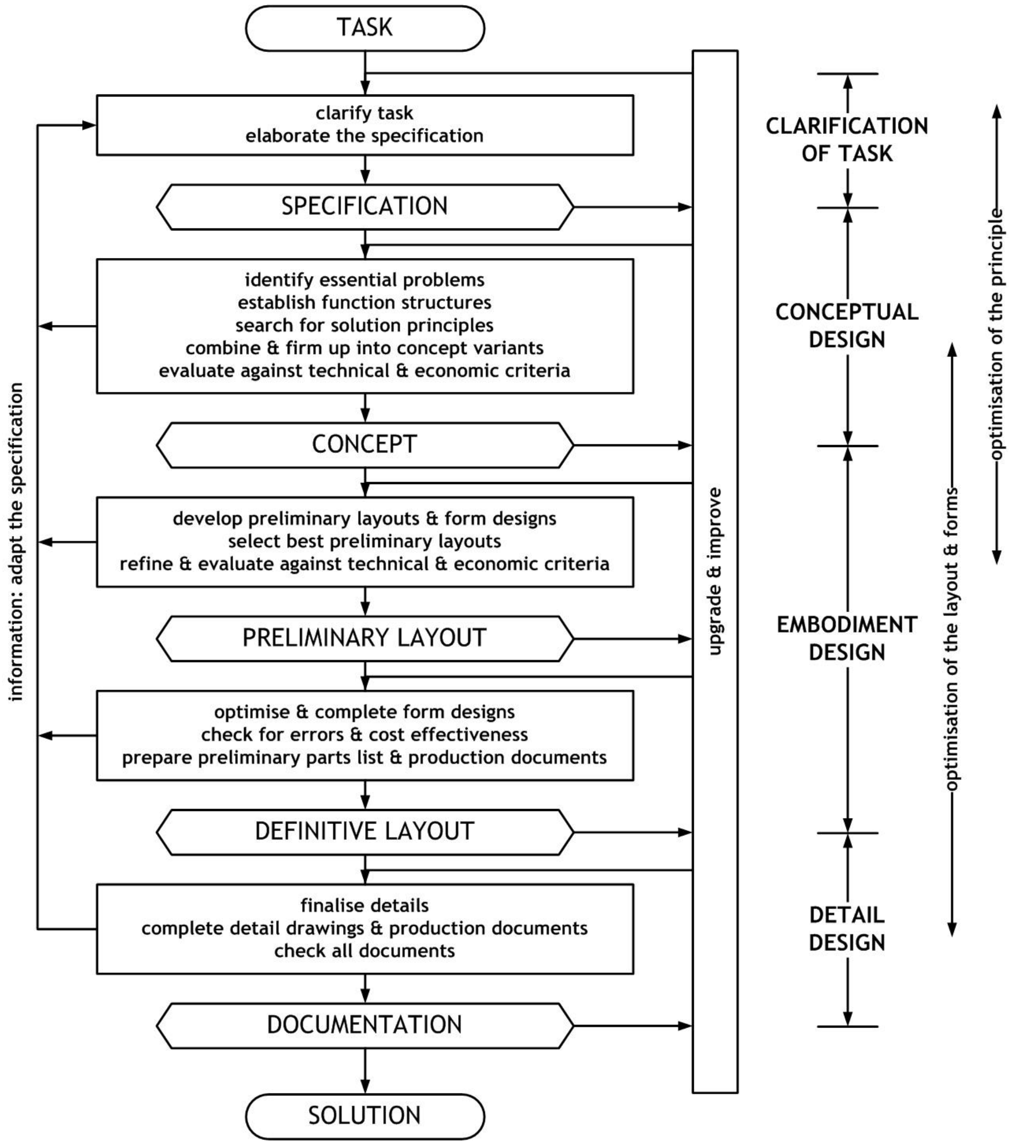

Figure 2-2: Pahl and Beitz's Steps of the Design Process (Pahl & Beitz, 1984, p.41).

Figure 2-2 also shows the process and phases of design as being summarised as two actions. They can be seen on the far right of the figure and are the actions of 'optimisation of the principle' and of 'optimisation of the layout and forms'. This is interpreted in the context of this thesis as describing the design process to simply be two-fold. That is to say, design is about optimising the principle of what is to be achieved and optimising the outcome in order to achieve this. This is a particularly abstracted viewpoint and the varying levels of abstractions within this model genuinely support an understanding of design at both an abstract and detailed level.

Albeit perhaps less popular than that of Pahl & Beitz (1984), there exist other models that also show design as a systematic or sequential process and use very similar phases. These phases are seen in the following designing models of this section and also to some extent in the section after which discusses descriptive designing models.

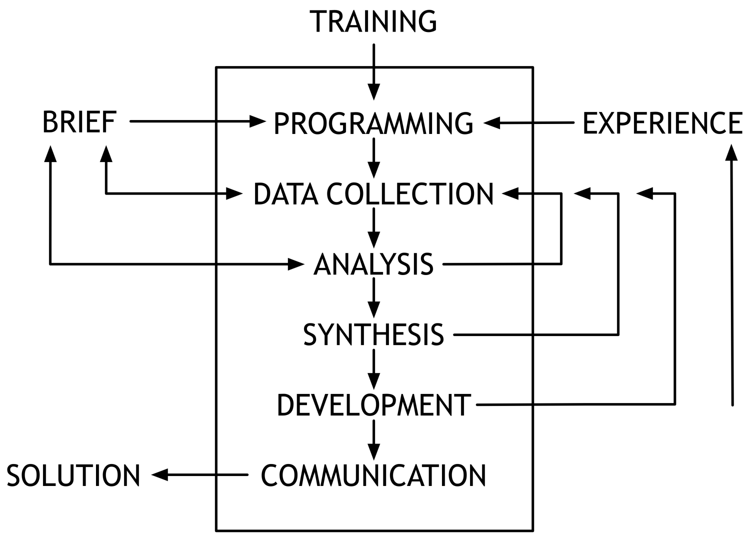

Figure 2-3: Archer's Model of Design Process (Archer, 1984 cited by Cross, 2000, p.35).

Archer

The model of designing process as produced by Archer (1984, cited by Cross, 2000) is shown in Figure 2-3. As individual elements, each step of the model is relatively easy to interpret. This is perhaps with the exception of programming which describes the action of proposing a programme and/or course of action for established design issues. Although it may initially seem dissimilar to that of Pahl & Beitz (1984), the elements of design activity identified within this model can be reduced to the same four abstracted phases of Pahl & Beitz (1984). In comparison, clarification of task may be considered as the collective effort of 'brief', 'programming', 'data collection' and elements of 'analysis'. Conceptual design is interpreted as being akin to the joint efforts of 'analysis' and that of 'synthesis' whilst embodiment and detail design are comparable respectively to 'development' and 'communication'.

The designing model here mainly differs from that of Pahl & Beitz (1984) by specfically considering external human and/or social influences. As seen in Figure 2-3, the element of practitioner 'training' feeds into the top of the complete designing process. In addition, throughout most of the designing actions, practitioner 'experience' can contribute or be gained at each step, or even as each step progresses to the next. The model also places strong emphasis on the design 'brief' which has significant importance for the entire process as it is seen to connect and extend to/from all initial designing actions or activities.

Archer's Three-phase

Archer also created an alternative to the designing model that was described in the previous section and explicitly removes the external elements of 'brief', 'training', 'experience', and 'solution', but retains the same central core of actions. It separates and summarises the designing process into three abstracted phases that are elaborated upon with detailed sub-actions. The three phases are described as 'analytical', 'creative' and 'executive'.

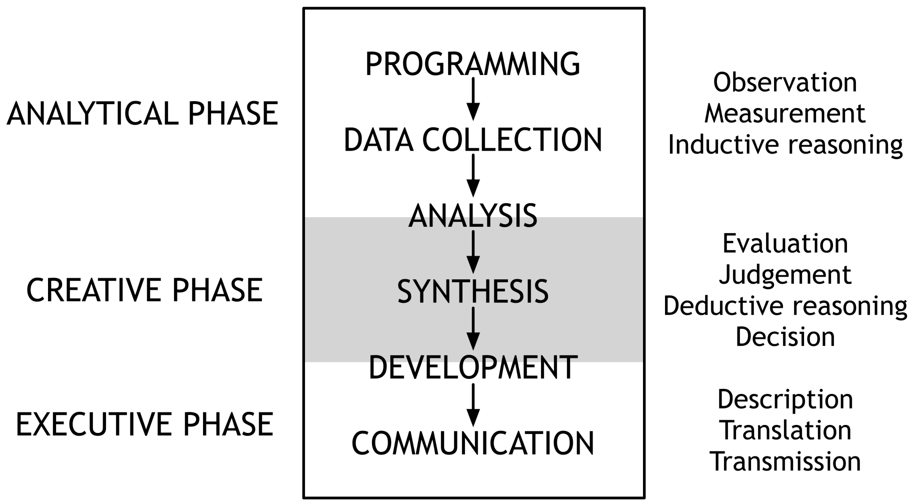

Figure 2-4: Archer's Three-phase Summary Model (Archer, 1984 cited by Cross, 2000, p.35).

Archer's three-phase summary model of the designing process can be seen in Figure 2-4 and shows its three phases to the left of the central core. If considering the designing process as these three abstracted phases alone, the model would be considered to be more descriptive in nature. This is arguably true of all prescriptive designing models that might be more simply described when summarised through its dominant phases of action.

Figure 2-4 also shows the more detailed sub-actions to the right of the central core. These are considered as elements of cognition, judgement, reasoning, and communication, which indicate that human and/or social considerations arguably remain acknowledged within the three-phase model. Using varying levels in the form of different actions and sub-actions to describe designing process, is also seen in the model of Pahl & Beitz (1984). More generally, it is considered to be a specific feature of models that are considered as prescriptive.

2.2.2 Descriptive Designing Models

Descriptive designing models are those that are formed from investigation and observation (Wynn & Clarkson, 2005). According to Cross (2000) they reflect a solution-focused approach in which there is emphasis in generating a solution concept early on. The models of French (1999), the Design Council (2005), Cross (2000) and Medland & Mullineux (1988) are examples of descriptive models. They are discussed here and are most simply, designing models that represent 'how design is and could be done'.

French

The design process according to French (1999) is shown in Figure 2-5 (p.13) as a block diagram in which the rectangular elements represent different phases of work and the circular elements represent their respective input and/or outputs. The phases 'analysis of problem', 'conceptual design', 'embodiment of schemes', and 'detailing' are directly comparable with the four abstracted phases shown in the systematic approach of Pahl & Beitz (1984).

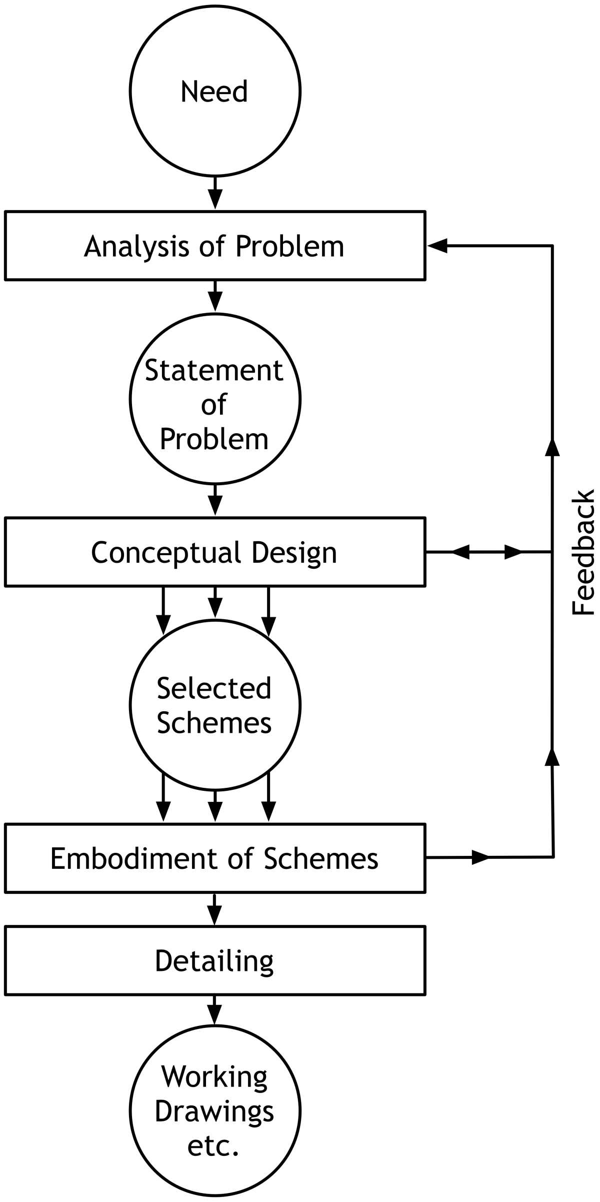

Figure 2-5: French's Design Process (French, 1999).

In comparison, it is evident that there is a strong likeness between the phases of work seen in Figure 2-5 and the four abstracted phases in the design steps of Pahl & Beitz (1984). This is to the extent that the design process by French (1999) might be described as a descriptive designing model for a prescriptive approach.

Design Council

The Design Council acknowledged that *"different designers manage the process of design in different ways"* and when assessing design practice within industry, observed *"striking similarities and shared approaches"* (Design Council, 2005). Their observations were captured and are communicated through the designing process model shown in Figure 2-6 (p.14).

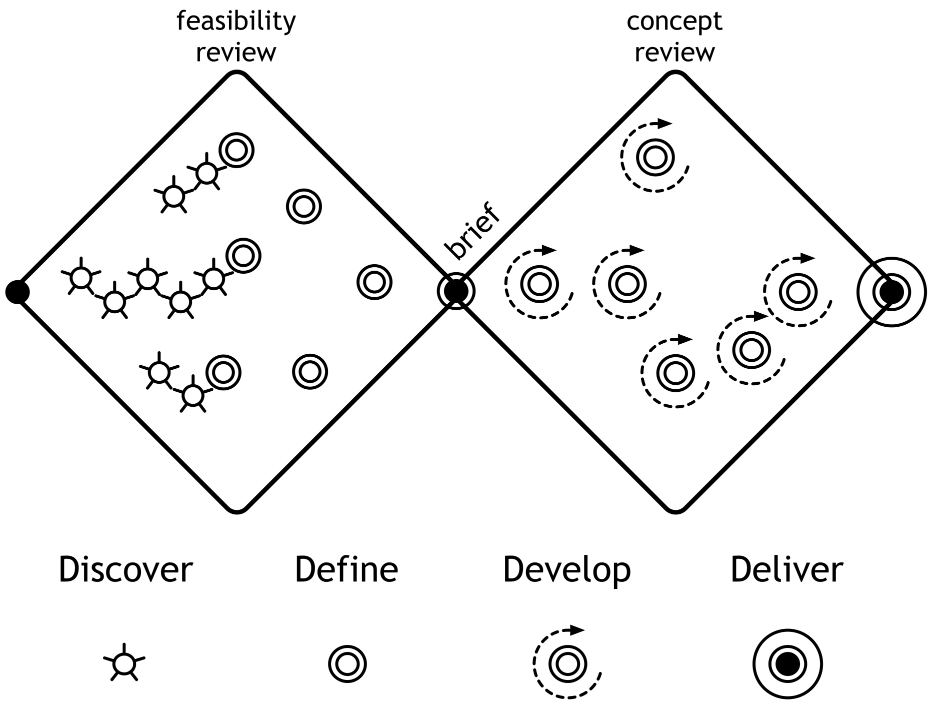

Figure 2-6: Design Council's Double Diamond Design Process (Design Council, 2005).

The Design Council (2005) maps the designing process as two diamonds that each represent a cycle of divergence and convergence. The elements that are shown within the diamonds represent ideas and/or instances that might evolve and contribute to the delivered design result. In Figure 2-6, the phases 'discover' and 'develop' are the divergences of the designing process, and 'define' and 'deliver' are their respective convergences. The figure also shows the discover-define diamond that describes the first half of the designing model as being predominantly shaped by 'feasibility review'. Such review is not only with regards to technical capabilites but with strong regards to designing in industry and therefore is also a feasibility review within the context of a business and commercial environment. It leads to the development of the (design) 'brief' shown as the midpoint of the process and similar to Archer (1984 cited by Cross 2000), the brief is again seen to be generally significant. It is then followed by the develop-deliver diamond as the second half of the designing model, which is predominantly shaped by 'concept review'. Furthermore, feasibility reviews that consider not only technical but also business/commerical feasibility, are particularly prevalent in industry-based designing models and/or processes.

When considering each of these divergence-convergence cycles, they may most simply be described as optimisation of the design principle and optimisation of the design form. This is notedly similar to the two most abstracted phases in the designing model of Pahl & Beitz (1984) and the 'optimisation of the principle' and 'optimisation of the layout and forms' respectively. As observed by the Design Council (2005), this supports the observation that the actions of different designing practice is not altogether that far removed.

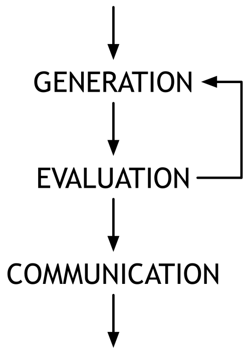

Figure 2-7: Cross's Simple Three-stage Model of the Design Process (Cross, 1989, p.20).

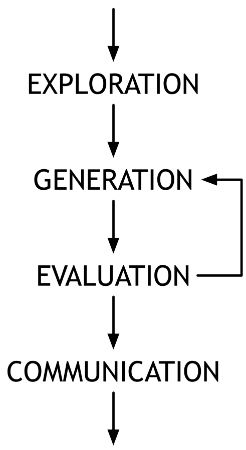

Figure 2-8: Cross's Simple Four-stage Model of the Design Process (Cross, 2000, p.30).

Cross

Shown in Figure 2-7, the early work of Cross (1989) is another example where the designing process has been described with a small number of only three phases. It descriptively sumarises the designing process as the phases of 'generation', 'evaluation' and 'communication' which are all directly comparable to those previously discussed as part of Archer's three-phase model. In a later development, the phase of communication is maintained, which reinforces the basic interpretation of design as *"creating a final description"* (Cross, 2000), although the phase of 'exploration' is added to complete the simple four-stage designing model shown that is in Figure 2-8.

Medland and Mullineux

The designing model described by Medland & Mullineux (1988) and shown in Figure 2-9 (p.16) demonstrates an emphasis on movement between the elements of 'concept', 'scheming' and 'analysis'. This loop then feeds into the elements of 'manufacture' and 'evaluation' and recursively so, thus representing an iterative nature to the designing process.

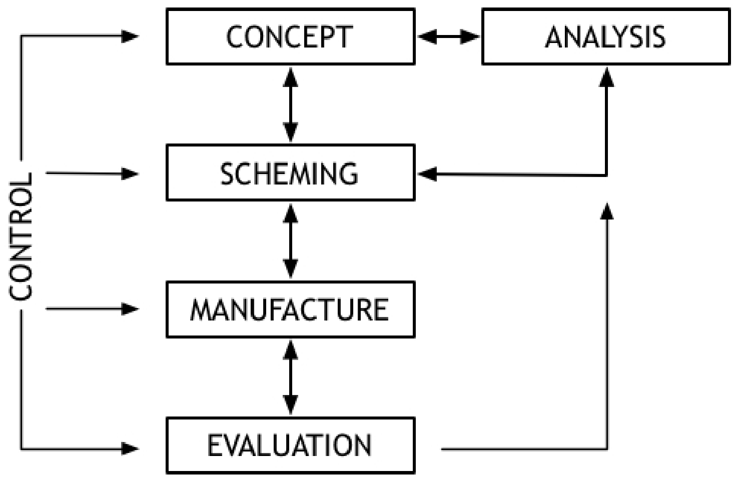

Figure 2-9: Medland's *"Design Process"* (Medland & Mullineux, 1988, p.9).

The model also shows an overarching element of 'control' that feeds into all aspects of the design process. For example, design requirements would have a controlling influence towards any of the phases shown. They would especially contribute towards the phases of concept and scheming and how the initial design solution would take shape. Design requirements and other possible elements of control are considered equivalent to being a form of imposed constraint. Most notably, this designing model, includes the element of manufacture as the realisation of design work into a physical form or final outcome that functions as intended.

2.3 Critically Comparing Designing Process Models of Engineering

Many reviews of different designing models have indeed previously been compared but with various motivations. As an example, Wynn & Clarkson (2005) explored the classifications of models in order to examine their practical relevance. Incidentally, as observed by French (1999), not all designing models are fitting for any given designing senario.

As proposed in Section 2.1.3 (p.7), and in agreement with Blumrich (1970) and Ullman (1997), this thesis supports the perspective that designing is closely related to general problem solving. In addition, the models initially examined in Section 2.2, notably show strong similarities between their phases of work, actions, and sub-actions. This has been seen across different designing models of both a prescriptive and descriptive nature. This thesis is therefore motivated to critically compare designing models in the context of basic problem solving. It also continues the aim to identify a common core or rather a collection of common features towards a simpler perspective of design.

This section introduces a problem solving perspective for comparing designing models. It discusses a problem-based approach to designing and designing as problem solving. It then critically compares the different phases of designing process against those of problem solving.

2.3.1 A Problem Solving Perspective Towards Designing Process

When considering a problem solving perspective, engineering design can be associated with being problem-based. In this thesis it is seen as simply a form of problem solving. This is not necessarily an agreed perception since many see design as something more - something that requires specific 'design skills' rather than being just about solving simple problems. The inherently similar nature between designing and problem solving or indeed designing as problem solving, is strongly advocated in this thesis.

Designing as specific tasks or elements thereof, are often referred to as 'design problems'. In the most simplest of terms, designing can be described as a process of finding a solution to a specific problem. The following sections explore the problem solving perspective towards general designing process and describes the subtle difference between a problem-based approach to designing and designing as problem solving.

A Problem-based Approach to Designing

Designing models have been classified as being either prescriptive (Section 2.2.1, p.9) or descriptive (Section 2.2.2, p.12) but, may also be described as either problem-based or solution-based approaches (Wynn & Clarkson, 2005).

A problem-based approach to designing places emphasis on the 'problem'. This means that the early designing effort is predominantly focused with understanding the issues of, and detailing the design problem and its structure. As a process, this is considered to be more linear. Generally progressing from problem to solution, any design iterations are more likely to occur between the different phases of work as part of the designing process. In contrast to this, a solution-based approach to designing places emphasis on the 'solution'. This means that the early designing effort is also focused on proposing a potential solution. In this case, both understanding of the problem and the solution development may occur somewhat simultaneously. As a process, this is considered to be especially iterative in which design iterations are more constantly between the design problem and one or more potential design solutions.

Regardless of whether a problem-based or solution-based approach to designing is applied, the actual design problem is pertinent to both. Without a problem, there is no solution to be created and/or developed. Therefore all design is problem-based in some way or another.

Designing as Problem Solving

Problem solving as a process has its own structure and specific set of actions. According to Ullman (1997), there are six phases of problem solving which are commonly followed by human cognition. Designing as a problem solving process involves the same phases but, they do not necessarily occur in a sequential way. Rather, the complete process goes through cycles of iterations that might recursively pass back and forth, and also between different phases of the process. Ullman (1997) also states that an iterative nature is what sets design apart from simple analysis and pure problem solving. The six phases of problem solving are 'establish', 'plan', 'understand', 'generate', 'evaluate', and 'decide', and described as follows.

- **Establish** a need or an acknowledgement that a design problem exists to be solved and/or any relevant designing criteria.
- **Plan** an initial approach, programme of actions, or a potential route to solution for the established design problem.
- **Understand** the problem by developing specific criteria and requirements, and investigating previous such problems or uncovering similar scenarios.
- **Generate** design proposals and alternative solutions as understanding develops in creating a preferred design outcome.
- **Evaluate** all proposals and alternatives in comparison to each other and against previously formalised design criteria and requirements.
- **Decide** upon a preferred design outcome from the available acceptable solutions or a solution that is most satisfactory.

When considering the perspective of designing as a problem solving process, according to Cross (2000) this list would be incomplete since design is also distinguished from pure problem solving by the additional phase of 'communicate'.

- **Communicate** the design decisions and the result of evaluations for justification of the finalised preferred design outcome and/or design recommendations.

When the six phases of problem solving are combined with the designing action of communicate, they still represent the problem solving process but also designing process. The same phases of work are common to both, hence, designing is seen as problem solving. This is further explored in the next section by comparing the phases of designing models against the phases of problem solving described above.

2.3.2 A Comparative Review of Designing and Problem Solving

In engineering design, many designing models can be more succinctly described by their general phases of work. In fact, there is even some agreement regarding four core designing phases that have been identified as 'analysis of task', 'conceptual design', 'embodiment design' and 'detailed design' (Howard et al., 2008). Whilst designing models, as in Section 2.2 (p.8), are commonly compared against each other, this section aims to examine their correlation with the seven phases of design-problem solving and hence, with a firm problem solving perspective towards general designing process.

In addition to those already discussed in Section 2.2, a number of designing models have been selected for comparison. Although varied, these are design-based and within the general remit of engineering design. For the comparative review, the process of splitting these designing models into appropriate phases of work, which this thesis refers to as 'abstract phases', and their associated elements, is described in the section as follows and with the review itself in the section after.

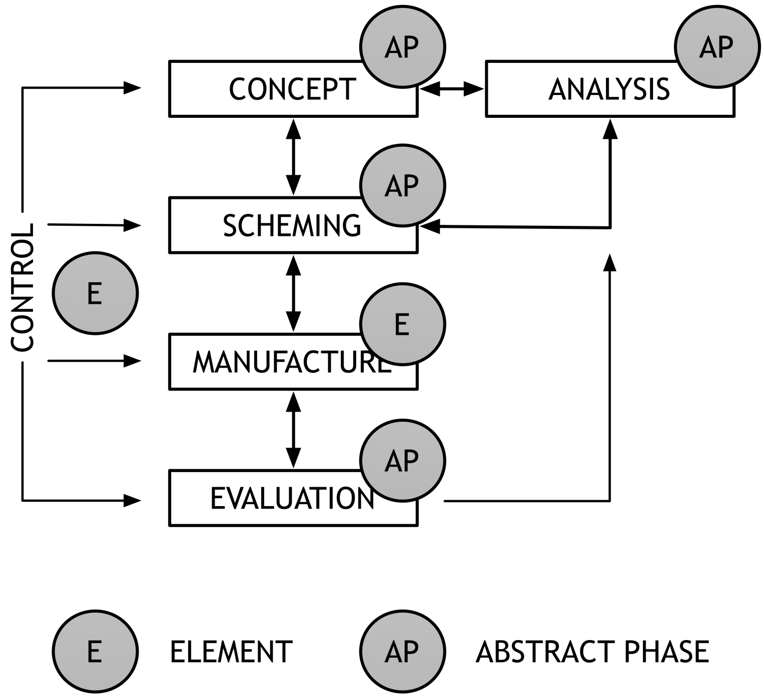

Figure 2-10: Interpretating Abstract Phases and Elements of Designing Process Models.

Defining and Extracting Abstract Phases for Review of Design Problem Solving

For the purposes of review in this thesis, each of the designing models have been split into a set of subjectively extracted phases and elements. Defined as an 'abstract phase', this describes part of a designing model at its most abstract, but actionable level. It is essentially the simplest possible action and/or sequence of actions, which can be used to describe or define a significant part of a specific designing process. In addition, defined as an 'element', this describes aspects of a designing model that contributes to the overall process but that does not necessarily form a significant phase of work that is actionable and defining in nature - it is not equivalent to an abstract phase. Figure 2-10 shows an example of how a designing model has been evaluated and split into 'abstract phases' (AP) and 'elements' (E).

Using the model as proposed by Medland & Mullineux (1988), it can be seen that when abstracted into different phases, the designing process is described by the instances of 'concept, analysis, scheming and evaluation'. The remaining and contributing elements are therefore 'control and manufacture'. For the declared elements, control is considered to be inherent in all the declared abstract phases. Since it is not a significant or standalone phase of activity, it has thus been classified as so. Manufacture is also considered as an element as it is more of change in hands and as such signals an end point to the engineering 'designing' process. However, it is recognised that manufacturing considerations must be made during design in order to be able to implement and realise the design solution in whatever form it may assume. This same approach of defining and extracting abstract phases, and any associated elements, has been applied to all the designing models critically and comparatively reviewed. The results of which are discussed in the next section.

Presenting the Observations and Review of Critically Comparing Designing Models Strictly Against the Phases of Design-problem Solving

For critical comparison, each of the designing models that are considered have been split into abstract phases and elements in a way, as previously described in the afore section. In some cases, the abstract phases are not necessarily that dissimilar to their original state. For example, the four key phases of Pahl & Beitz (1984) are an abstraction that has not been interpreted any differently from the original model. However, in some cases, abstract phases have been additionally assigned. An example is the designing model, VDI 2221 (1973) and its inherent likeness to the phases of Pahl & Beitz (1984).

The results of the comparative review between designing models and the phases strictly described as design-problem solving are shown in Table 2.1 (p.21). Note that the total number of abstracted phases is denoted 'AP' and the total number of elements is denoted 'E'. For each of the designing models reviewed, any abstract phases are described in the upper line and in bold tex. Any elements are described in the lower line and in normal text. Both abstract phases and elements of the designing models are placed under the phase of design-problem solving with which they are most relevant.

Not shown in Figure 2.1 is the iterative nature of designing models. However, it is noted that each of the models are in fact all iterative in some way. As previously noted design iterations can occur within individual abstract phases. They are also equally likely to occur between various different phases and are mainly limited by how designing processes advance and move towards a preferred design solution.

Whilst classifying designing models into respective abstract phases and elements for comparison, most instances required careful inquiry in order to correctly place them against the relevant phase of design-problem solving. In doing so, it was therefore observed that designing models are not always as heuristic as they might inherently tend to be. To this extent, such models require some level of basic understanding or even study in order to maximise their effectiveness. As such, it also supports the idea that designing models are most practical for those with what Ullman (1997) describes as 'domain knowledge' and, an existing understanding of what is relevant to the context of a specific designing process.

The critical comparison of abstract phases and elements of different designing models demonstrate that each aspect is comparable in some way to one of the seven phases of design-problem solving and to problem solving process in general. What is most evident, is that the majority of the abstract phases and/or elements predominantly falls under the phase of 'understand' and followed by the phases 'generate' and 'evaluate'. Interpreting these phases as being core actions, designing may be viewed as a process of 'understanding' a design problem, 'generating' preferred solutions, and then 'evaluating' their appropriateness. As a further thought, if the viewpoint of French (1999) were to be considered, evaluation would be considered as a continuous activity that would then form an element rather than an abstract phase. Hence, designing would then predominantly be a core action of understanding a design problem and then generating a response in the form of a preferred design solution.

DESIGN MODEL		ESTABLISH	PLAN	UNDERSTAND	GENERATE	EVALUATE	DECIDE	COMMUNICATE
RIBA Handbook (1965)	AP 4 E 4			**assimilation / general study**	**development**			**communicate**
Markus/Maever (1969/1970)	AP 4 E 7			**analysis**	**synthesis** proposals / scheme / detail	**appraisal**	**decision**	
Hill (1970)	AP 3 E 6			**identification of need** state-of-the-art	**conceptualization** production	**feasibility analysis**	acceptance	
VDI 2221 (1973)	AP* 4 E 9			**clarification** task / clarify / determine	**conceptual / embodiment / detail** search / divide / develop		complete	prepare / realization
Darke (1983)	AP 3 E 3			**generator**	**conjecture**	**analysis**		
Dieter (1983)	AP 5 E 6	**recognition of need**	gathering information	**definition of problem**	**conceptualization**	**evaluation**		**communication**
Archer (1984)	AP 3 E 6			**analytical** programming / data collection	**creative** analysis / synthesis / development		**executive**	communication
Jones (1984)	AP 3 E 3			**analysis**	**synthesis**	**evaluation**		
March (1984)	AP 3 E 9			**production** models / describe / design	**deduction** performance / predict / theories	**induction** characteristics / evaluate / suppositions		
Pahl & Beitz (1984)	AP* 4 E 7			**clarification** task / specification	**conceptual / embodiment / detail** concept / preliminary / definitive			documentation / solution
French (1985)	AP 4 E 8	need		**analysis of problem**	**conceptual / embodiment / detail**	statement of problem	selected schemes	working drawings
Medland (1988)	AP 4 E 6			**analysis**	**concept / scheming** manfacturing	**evaluation**	control	
Cross (1989)	AP 3 E 3				**generation**	**evaluation**		**communication**
Pugh (1990)	AP 4* E 6	**market** sell		**specification**	**concept / detail** manufacture			
Ulrich & Eppinger (1995)	AP 5 E* 6		**planning**		**concept / system / detail**	**testing**	refinement	
Cross (2000)	AP* 4 E 4			**exploration**	**generation**	**evaluation**		**communication**
Double Diamond (2005)	AP 4 E 7			**discover / define** feasibility review / brief	**develop**	concept review	**deliver**	
RIBA Work Stages (2007)	AP* 5 E 11			**preparation** appraisal / brief	**design / pre-construction** concept / development / technical / info / document / tender	**use** post practical		**construction** mobilisation / completion

Table 2.1: A Comparative Review of Designing Models and their Abstract Phases and Elements Against the Phases of Design-Problem Solving.

In applying the perspective of designing as problem solving, it can indeed be described by the actions defined by Ullman (1997) and also described by the phases of design-problem solving as listed here in this thesis (Section 2.3.1, p.17). As a result of critical comparison, the likeness between the abstract phases of the designing models and the seven phases of design-problem solving are so great, that the latter may be concluded as equivalent to being a collection of common actions that make up any designing process. Overall, it has been seen that designing and problem solving are closely related and this can contribute to a simpler perspective towards design thinking.

2.4 A Cognitive Perspective Towards Designing

In the previous section, designing and problem solving have been shown to be closely related. Further to this, creativity is considered to be pertinent to designing practice. For the most part, creativity and problem solving are perceived to be very similar cognitive activities. This section therefore seeks to identify a relationship between the creative-problem solving process and design-problem solving. It begins by examining cognition within the scope of engineering design, followed by the elements of creativity, innovation and knowledge which are all considered to contribute to designing in general. The latter part of this section links these together with an emphasis on the phases of design-problem solving (Section 2.3.1). Overall, the section supports the idea that creativity, designing and cognition are all linked.

2.4.1 Cognitive Processing

The nature of problem solving is fundamentally attributed to our cognition. It is simply down to the way we think. Ullman (1997, p.51) goes as far as saying that, *"all humans have the same cognitive or problem solving structure"*. Therefore, cognition as the action of processing information and experience, has its bearing upon ability to design and solve problems. According to Dieter (1991), the human mind may be compared as being a *"three-element computer"*. The parts are described in the following list.

- **Preconscious Mind -** A storehouse of knowledge based on education and experience.
- **Conscious Mind -** Compares the preconscious with the external reality presented.
- **Unconscious Mind -** Acts between both the conscious and the preconscious mind.

Furthermore, each part can also be described by the extent of what may or may not be known, or, what is yet to be known. The 'preconscious mind' can be described as what one thinks is known. The 'conscious mind' can be described as being between what one thinks is known along with what is known, and the 'unconscious mind' can be described as either what one does not know is known or what is yet to be known. Together, the three parts form an in-the-mind process in which the 'unconscious mind' somehow connects the realities of a design problem taken on by the 'conscious mind' with the education and experience of the 'preconscious mind'. Whilst these parts describe what happens within our minds, it is not precisely known how, but there is an opportunity to support and hence, connect the knowns and unknowns of a design problem, in order to support designing process, in general.

Cognition or cognitive processing is important to how problems are approached and solved. Hence, it is closely related to designing and design-problem solving, and also shares strong similarities with creative-problem solving. Both are in-the-mind processes. Therefore, the following sections explore creativity, innovation and knowledge, as the elements that are fundamental to the different minds of cognitive processing in the context of designing.

2.4.2 Creativity and Innovation

Engineering design is often said to be synonymous with creativity and innovation. Sir George Cox, former chairman of the UK Design Council, defines design as *"that which links creativity and innovation"* (Cox, 2005). While this may or may not be true, creativity and innovation are certainly pertinent. They are themselves, the subject of much interest for various communities. Historically, there is also a demand for 'creative' and 'innovative' results from design practitioners, for example, in order to gain competitive advantage.

As terms, creativity and innovation are often bandied around. On occasion, albeit mistakenly, they may be considered to be one and the same. There is however, a distinct difference between the two, yet it is difficult not to use one without the other as they are so closely linked - *"there is no potential for innovation without creativity"* (Howard et al., 2008, p.160).

Creativity in the Context of Designing

Creativity is an ability to produce something that is new and unique but in keeping with the specific context at hand. The idea of 'creative design' is effectively summarised by Niku (2009, p.5) as the result of being *"uniquely appropriate for the problem"*. Here, and for the interpretation in the context of this thesis, the emphasis of creativity leans more towards being 'uniquely appropriate'. This is rather than solely being something new, or original. At this point, it is noted that what may be new to some, may not be new to others. Hence, originality is simply not enough when attempting to define something as being creative.

Regardless of this fact, different types of engineering design have been previously classified according to the principle of originality - the reason perhaps being because originality as a result of designing process is so keenly sought after. The different types of design, described as one of three outcomes, extend from the ideas developed by Wögerbauer (1943 cited by Pahl & Beitz, 1984) and Opitz (1971 cited by Pahl & Beitz, 1984) and have since been formalised by Pahl & Beitz (1984) as being original, adaptive and/or variant design. The different types of design outcome have been interpreted here in this thesis and simply classified as being different kinds of design. They are described in the following list.

1. **First-of-its-Kind** - Original design in which the solution principle may be considered as a foundation or as part of other design work or for future development.

2. **One-of-a-Kind** - Unique design in which the solution principle is specifically appropriate to a particular context and/or principles that dictate design reasoning.

3. **Similar-in-Kind** - Adapted design in which the solution principle is achieved by adapting aspects in order to facilitate a like-for-like quality from previous designs.

Design described as the 'first-of-its-kind' is considered to be quite a rare occurance. It is a particularly difficult kind of design to achieve and is considered as being revolutionary in nature. Design described as 'one-of-a-kind' is considered to be more of a significant step change and innovative in nature. (Innovation is further discussed in the next section.) It is closely related to design described as 'similar-in-kind' which is considered evolutionary in nature, in terms of incremental improvement.

The preferred solution or outcome of a specifically defined design problem is considered not only to be one of the types listed in this section, they are also all considered to be creative. They will each be 'uniquely appropriate' to very specific criteria which is unlikely to be identical in every aspect to another. Hence, all design is creative.

Innovation in the Context of Designing

Innovation is the application of existing methods or knowledge in a novel and unique approach. Niku (2009) makes the distinction between innovator and inventor as one who practises designing differently. This is in order to create a competitive edge over one who practises designing in an original way. This is very different to creativity, but similarly it does not always provide new inventions or original design. Innovation is effectively described as *"the intersection of invention and insight"* by the American National Innovation Initiative (2005 cited by Niku, 2009, p.6).

By the interpretation within this thesis, it is seen that innovation is rooted in knowledge. This is also considered to be true for creativity. This is especially since what is creative, is party dependent on what is known as new, and what might be known to some but not known to others. In this way, both creativity and innovation are consistently influenced by the information available to practitioners and the knowledge they have previously acquired, or have yet to acquire when design-problem solving.

2.4.3 Knowledge

The value and management of information and knowledge developed within designing process is acknowledged by Ullman (1997) and his perspective of design as *"the organization and the management of people and the information they develop in the evolution of a product"* (Ullman, 1997, p.7). The effective use of knowledge is also considered to be critical towards increasing capabilities of competitive advantage and innovation (McAlpine, 2010).

Knowledge is derived from data and information. Data is defined as a collection of *"unstructured facts or figures"* (Thierauf, 1999, p.6) that are simply *"without context or discernable meaning"* (McAlpine, 2010, p.26). It is different to information, which is most regarded as being contextual and structured data (Thierauf, 1999, p.7) that provides purpose and meaning (Davenport & Prusak, 2000). Unlike data and information, knowledge cannot be 'automatically generated'. It is described by Nonaka (1994, p.15) as a *"multifaceted concept with multilayered meanings"* and by (McAlpine, 2010, p.26) as *"the internal belief state of a person"*, which is shaped by the education and experience of the individual and/or their community. Knowledge is undoubtably a valuable commodity in designing.

Attempts to classify different types of knowledge have been made for centuries, and as far back as the Greek philosopher Aristotle. More modern classifications such as that of Ryle (1949, cited by McAlpine, 2010), provide a simple distinction between the two types of knowledge, 'know-that' and 'know-how' which are described in the following sections.

Explicit 'know-that' Knowledge

Explicit or know-that knowledge can be formalised and is easy to share, transmit or receive (Nonaka, 1994). It is what McMahon & Draper (2002, p.69) describe as 'embedded' or 'encoded' knowledge. It is represented through signs or symbols within books, manuals, and recorded works, and is also the type of knowledge that is found and often becomes rooted within formal repositories such as systematic routine, procedure, and practice (Davenport & Prusak, 2000). As a commodity, it is possible to exploit knowledge that is more explicit. Examples of attempts to formally externalise designing knowledge has been seen in the designing process models seen in Section 2.2, and which significantly contribute to knowledge in designing and engineering design, in general.

Tacit 'know-how' Knowledge

Tacit or know-how knowledge is especially difficult to share or even formally externalise (Polyani, 1966). As such, it is *"deeply rooted in action, commitment and involvement"* (Nonaka, 1994, p.16). Types of tacit knowledge are what McMahon & Draper (2002, p.69) describe as 'embrained' or 'embodied'. It is found in an individual's ability and practical thinking, and most likely gained through personal experience. As a commodity, it is more difficult to take advantage of and arguably the most valuable type of knowledge.

With respect to both explicit and tacit knowledge, explicit knowledge gained does not necessarily facilitate or mean that tacit knowledge might also be gained (Polyani, 1966). However, a combination of explicit and tacit knowledge is possible and is described as 'encultured' knowledge. It is found within the process of *"achieving shared understanding"* (McMahon & Draper, 2002, p.69) and extends from practice and/or experience.

2.4.4 Designing as a Creative and Cognitive Process

In the previous sections, cognition is considered an important influence on design-problem solving. The equally important elements of creativity, innovation, and knowledge were also examined. The latter being very much a fundamental connection between all of these. In this section, creative-problem solving is firstly explored and then compared with designing and cognitive processing in order to demonstrate that they are inextricably linked.

The Creativity Process as Creative-Problem Solving

Previous attempts have sought to describe the creative process with as much vigour as those who have attempted to describe designing (Howard et al., 2008). Formalised by Wallas (1926) and arguably the most commonly accepted, Figure 2-11 (p.26) shows the creativity process described by the phases of 'preparation', 'incubation', 'illumination', and 'verification'.

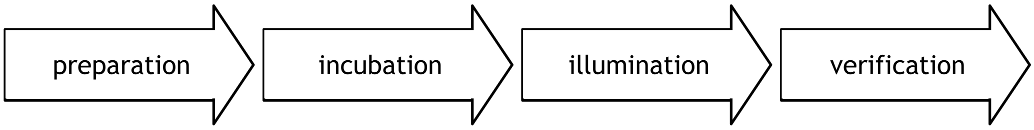

Figure 2-11: The Creativity Process and Phases of Creative-Problem Solving.

The process shown in Figure 2-11, represents not only the creativity process but is also equivalent to creative-problem solving. The process begins with the preparation phase in which the problem is explored, defined, and fixed with specified objectives. In the same phase, associated elements and interrelations would also be considered within the context of the problem and the knowledge or understanding of those involved. As part of the incubation phase, no conscious cognitive actions are made and a step back may be taken from problem solving to the extent that one *"sleeps on the problem"*. This in part, allows for the unconscious mind to take over. Following some period of time, there is a flash of insight which results in an idea or even series of ideas to suddenly emerge. This is described as the illumination phase which can be best described as a 'eureka moment'. The in-the-mind process that does indeed generate ideas as part of illumination cannot be explained which has historically been held against the creativity model itself (Guilford, 1950 cited by Lubart, 2001, p.295). In the final phase of creative-problem solving, the illuminations that have yielded ideas are put through the 'verification' phase. They are tested for their appropriateness against the original problem objectives of the preparation phase although, it is entirely conceivable that illumination may not always yield a satisfactory outcome. Hence, the process would then be repeated until verification yields sufficient satisfaction. In this way, creativity processes are invariably iterative in nature.

Creativity, Designing, and the Cognitive Process

In this section, creativity, designing, and cognitive process, when compared, are considered as being closely linked to each other and also to problem solving. The phases of creative-problem solving as creativity, design-problem solving as designing, and cognition as the cognitive process are shown against each other in Table 2.2 (p.27).

In Table 2.2, it is shown that 'preparation' as a phase of creativity is in align with the 'establish', 'plan', and 'understand' phases of designing, which in turn is in align with the efforts of the 'conscious' mind. Also drawing on the efforts of the conscious mind is the creativity phase of 'verification' which, with respect to the designing process, is considered comparable with the phases of 'evaluate', 'decide', and 'communicate'. The 'incubation' and 'illumination' phases are deemed as those respectively under the influence of the 'pre-conscious' and 'unconscious' mind. They are the phases that are precisely and specifically unexplainable, but are equally important to the results that eventually yield a satisfactory outcome for the problem solving process. The preconscious mind is arguably equivalent to the storehouse of knowledge that supports the illumination phase of creativity in which knowledge is then externalised through the unconscious mind. This allows for one or several ideas to be generated and hence, are in align with the 'generate' phase of designing.

CREATIVITY PROCESS	DESIGNING PROCESS	COGNITIVE PROCESS
preparation	establish / plan / understand	conscious
incubation	generate	preconscious
illumination		unconscious
verification	evaluate / decide / communicate	conscious

Table 2.2: Creativity, Designing, and Cognitive Processes.

When considering the observations made in reviewing designing models (Section 2.3.2, p.20) and the comparison of creativity, designing, and cognitive process in this section, the initial effort in creative 'preparation' and of the 'conscious mind' strongly supports the design-problem solving phase, 'understand'. It also reinforces the emphasis of understanding in design-problem solving. In the context here, designing process can be described as activities of preparation towards facilitating shorter incubation and quicker illumination phases for iterative cycles of design, in which the outcome is verified through a final evaluation stage before being communicated.

Overall, the likeness between creativity, designing and cognitive process are indeed all closely related, to the extent that they might all be considered as forms of problem solving. This thesis supports the notion that *"design is a quintessential cognitive task"* (Goel & Pirolli, 1992, p.395) and also creative. Although there is some dispute as to how processes are defined as either creative or non-creative (Lubart, 2001), designing when considered as a problem solving process that searches for 'uniquely appropriate' solutions, is indeed creative. Fundamentally, creativity, designing, and cognitive process are also linked by knowledge and understanding.

2.5 Chapter Conclusions

In this chapter, designing has been explored with the simpler perspective of being a problem solving process. It has compared various designing models against seven phases collectively identified as design-problem solving. As such, it has been concluded that these phases are indeed common actions that describe designing, of which understanding is a particularly prominent phase. It has also explored the elements of creativity and innovation that are considered closely associated, or even synonymous with general designing process. As a result, it has been demonstrated that design-problem solving and creative-problem solving are indeed closely related. They are both considered inextricably linked to cognition or by cognitive process, of which knowledge is the underlying connection. The simplicity of these conclusions are considered valuable, especially with the constantly evolving challenges and increasing complexity in designing.

The next chapter continues by maintaining the perspective of designing as problem solving and explores the principles of constraints and constraint-based thinking as a complementing approach with potential in enhancing and supporting designing.

Chapter 3

Constraints, Constraint-based Approaches, and Constraint-based Thinking

"I am always doing that which I cannot do, in order that I may learn how to do it" - Pablo Picasso.

Design-based practices are in all cases subject to constraints which have a significant impact on designing and the results thereof. This chapter firstly examines the fundamental nature of constraints and constraint-based approches and then continues whilst maintaining the previous chapter's perspective of designing as problem solving. It proposes constraints as a means of facilitating understanding and explores constraint-based thinking for its potential to complement designing and design-problem solving including elements such as creativity.

3.1 Understanding Constraint-based Thinking

Constraints are by their own nature, *"ubiquitous in decision problems"* (O'Sullivan, 2002). However, the general approach to handling constraints is not always positively driven. This thesis views constraint-based thinking as a means of applying the mindset in which constraints become proactively acknowledged, formally identified and, as a result, the consequent handling of constraints specifically become integral to problem solving processes which would include design-problem solving and engineering design. This section firstly examines what a constraint is, from where constraints arise, and what constraint handling means. Finally it considers the general phases that contribute to a constraint-based approach, basic constraint handling methods and computer-aided support.

3.1.1 A Simple Perspective of What a Constraint is

Constraints are some form of restriction or simplification, real or artificial, that simply bounds what can be done (Mullineux, 2001). Such constraints consistently impose upon every instance of decision-based problems and also upon general problem solving processes.

Overwhelmingly, general perspectives and the interpretation of constraints as *"barriers or strictures"* (Stokes, 2009) demonstrates a bias towards constraints that has less than favourable connotations. However, constraints are not just the strictures that they are so commonly perceived to be. In this thesis, they are considered to be highly functional, especially with respect to enhancing and supporting designing and design-problem solving.

3.1.2 Where Constraints Arise From

Although they are predominantly seen to be some form of restriction or simplication that set boundaries or limiting conditions, constraints arise in various ways. First and foremost, they extend from physical and natural laws such as 'Newton's Laws of Motion', or the 'Laws of Thermodynamics'. They also extend from the laws and/or principles governing conduct such as legislation and statutory requirements.

Constraints can also arise as a result of complexity and the interaction of two or more parts, for example, of a design problem during any phase of designing process. With specific respect to design-problem solving, constraints can be derived from a project's design brief and its technical specification (Mullineux et al., 2005), or from the demands, as wants and wishes, of a customer. In this way, constraints represent declared objectives and requirements in the form of what is to be achieved, information relevant to this, and even aspects such as solution properties. It is important to note that although constraints might be able to describe what needs to be achieved, individually they cannot be used to explicitly describe how. (Hicks et al. 2006; Yan & Sawada 2006; Buscemi & Montanari 2008).

3.1.3 What Constraint Handling Means

When constraints represent restrictions or objectives, they often present conflicts that respectively need to be resolved or problems that requiring solving. The direct handling of constraints forms the basis of a constraint-based approach in order to resolve conflict or satisfactorily achieve objectives and their associated requirements. It is a process in which the intended outcome aims for constraints not to be violated, and either resolved or satisfied.

As part of a constraint-based approach, the general handling of constraints that are indeed either resolved with respect to any conflicts or satisfied with respect to specific objectives or requirements, is in many ways dependent upon the nature of the individual constraints themselves. Constraints may be interpreted as being either 'hard' or 'soft'. In these states, they are respectively comparable to 'design wants' that must be achieved, and 'design wishes' that are ideally achieved. Hard and soft constraints are described in the following sections.

Hard Constraints

Hard constraints are identified as being those that must be completely satisfied, and where violation of the constraints is not acceptable (Régin, 2004). They predominantly include constraints that are based upon physical and natural laws. In addition they hold a 'global' influence. That is to say, their influence must consistently and continuously be considered within the entire context of the decision problem, or, for example, in all phases of design-problem solving and the complete designing process.

Soft Constraints

Soft constraints are commonly identified as being those that are to be satisfied but, where violation of the constraint is, to some degree, considered acceptable (Régin, 2004). They are said to express preference (Buscemi & Montanari, 2008) as opposed to being explicit mandatory achievements. In addition, they hold a 'local' influence. That is to say, their influence is only considered to be relevant within the immediate context of the decision problem in which they are declared, or, for example, in one specific phase of design-problem solving and at a specific point or interval of the designing process.

For soft constraints, the occasional exception might be granted in which such constraints are redefined and promoted to holding a global influence. This may be for a particular line of inquiry or a customised approach (Régin, 2004). If this were to be the case, soft constraints are only global if specified as being so and only for the length of the respective inquiry.

Phases of Constraint Handling as a Simple Constraint-based Approach

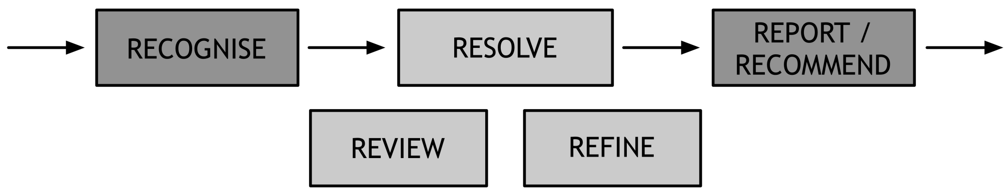

Figure 3-1: The Phases of a Simple Constraint-based Approach.

Figure 3-1 shows the general phases of constraint handling that contribute to, or rather form a simple constraint-based approach. In the first phase, constraints are acknowledged and one must 'recognise' what constraints exist and the nature of these. For example, the constraints that arise should be noted as being either hard or soft constraints, whether or not they are conflicting with each other, or, if they conflict with any objectives and/or requirements.

The second phase consists of the actions 'resolve', 'refine', and 'review'. In most instances, resolving constraints in conflict and ensuring that they are not violated and hence satisfied, is an iterative process. In addition, constraints or requirements are often refined and reviewed in order to facilitate as much as possible, circumstances in which full constraint resolution occurs. During iterations of refine and review, additional constraints may also emerge as understanding is increased. The phase in which constraints are resolved, and how they are actively used in order to do so, is the essence of any constraint-based approach. It is the phase that most significantly varies between different approaches in constraint handling.

The third and final phase of a constraint-based approach is described by the actions 'report' or 'recommend'. In the instance that all constraints are resolved and satisfied, this is reported as a satisfactory result. However, in the instance where some constraints may still cause conflict or remain unsatisfied, the most satisfactory result would then be recommended.

3.1.4 Basic Approaches to Constraint Handling

When constraints are available and their validity can be tested, three basic approaches to constraint handling have been identified (Matthews, 2007), and are described as follows.

- **Constraint Checking** - The simplest means of constraint handling. Each constraint is tested in turn using the most current design variables and any violations are simply reported.
- **Constraint Satisfaction** - The next level up from constraint checking. In most cases, computer-based support is used to investigate variables in attempt to satisfy all imposed constraints.
- **Constraint Optimisation** - Includes constraint checking and techniques for constraint satisfaction. However, the overall aim is to satisfy all imposed constraints 'and' to some extent, satisfy one or more measures of performance and therefore optimise.

3.1.5 Constraints and Computer-Aided Support

The advent of computer-aided design (CAD) has seen the development of tools which have evolved with parametric (Rudolph & Blling, 2004) and feature-based capabilities (Singh et al., 2006), and the application of constraints to ensure geometric entities maintain appropriate relationships to each other (Martínez & Félez, 2005).

Various computer-aided tools have evolved in support of designing, troubleshooting, and problem solving. This includes constraint modelling which is concerned with formalising and representing the relationships of variables that arise. Modelled as sets of inter-related constraints that may include conflicting requirements, and as a series of connected relationships, this allows for the investigation of a set or rather network of constraints.

The advantages of constraint modelling mean that an increasing number of constraints can be explored, and to some extent automatically. Any investigated constraint sets are also more easily remembered and recalled. Furthermore, the use of symbolic logic and numeric mathematical operations and general (constraint) programming has led to the development of effective constraint-based solvers. Each offers a different approach to constraint handling, some of which are described below.

- **Parametric Solvers** - Solves constraints in an explicitly defined sequence.
- **Variational Solvers** - Solves constraints but not necessarily in a sequential manner.
- **Top-down Solvers** - Solves by isolating constraint sub-problems and then recursively reconstructing. These solvers naturally recognise over-constrained problems.
- **Bottom-up Solvers** - solves by recursively dissecting the constraint problem with respect to sub-problems. These solvers naturally recognise under-constrained problems.

For the constraint solvers described above, the basic underlying concept of how a constraint problem is solved as a constraint-based approach, is not necessarily specific to only constraint problems. The nature of designing as a problem solving process and constraints being ubiquitous to all decision-based problems means that there is potential for methods of constraint handling such as constraint solvers and their general principles to also be generally applied to design-problem solving. The next section examines constraints and designing more closely and how constraint-based thinking that is mindfulness of constraints and constraint handling might be applied in order to enhance designing and design thinking.

3.2 A Constraint-based Approach Towards Designing

The ubiquitous nature of constraints in decision-based problems means that constraints will indeed arise in all design-based practices. It provides a basis for exploring constraint-based thinking from which constraint-based approaches have emerged and also in the specific context of designing and design-problem solving. Continuing to maintain the perpsective of designing as problem solving, this section continues by examining constraints that can be described using regions of design space and how constraints and design spaces can be used to describe different problem types. This is then followed by examining the nature of constraints and how this is useful in creating or describing design-problem structures. Finally this section explores the many ways in which constraints can be used in order to support understanding towards enhancing designing, and towards optimisation in designing.

3.2.1 Constraints and Design-Problem Solving Space

Constraints naturally arise in all areas of design-problem solving and constraint-based techniques have consequently arisen to support this. In some instances, a constraint can be regarded as a relationship between certain design parameters that correspond to a region of design space in which the constraint is satisfied. In this way, different constraints correspond to different regions and a fully satisfactory design solution is that which lies at the intersection of all regions. This is shown as the 'constraint space intersection' in Figure 3-2.

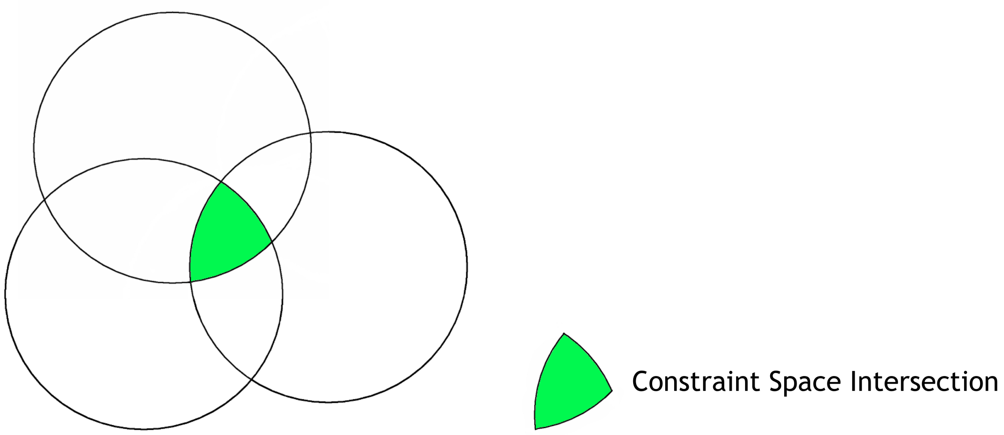

Figure 3-2: Satisfactory Design Solution as Constraint Space Intersection.

In addition to describing design space and the regions thereof, constraints can also be used to describe three different problem types that have been identified (Hoffmann, 2005), and are described as follows.

- **Over-Constrained Problems** - Such problems have no acceptable solutions. With respect to Figure 3-2, the constraint space intersection would be empty. They are also considered to be rigidly structured problems and highly complex.
- **Under-Constrained Problems** - Such problems have an infinite number of acceptable solutions. However, they may also be problems that have unacceptable solutions which have been allowed, for instance, in cases where constraints are intentionally omitted. They are also considered to be ill-structured problems and lack complexity.
- **Well-Constrained Problems** - Such problems have a finite number of solutions that are all acceptable. With respect to Figure 3-2, the constraint space intersection would be similar. They are also considered to be well-structured problems with manageable complexity.

3.2.2 Constraints, Design-Problem Structures and Understanding

In the previous section, design problems were described with respect to design space and with respect to how they were constrained. In comparison, this section firstly considers how constraints can be used to describe the design-problem structure and then explores how constraints can generally support understanding towards enhancing design-problem solving.

Describing Design-Problem Structures with Constraints and Investigating the Design Space

With respect to engineering design, efforts have been made to define and investigate design spaces and the very closely related design-problem structures (Goel & Pirolli, 1992 and Jonassen, 1997). Such efforts are mindful of the early work by Newell & Simon (1972) and their investigation into human problem solving.

As a simple action, albeit a significant one, problem structuring is fundamentally different to problem solving (Goel & Pirolli, 1992). It draws upon the knowledge available at any given time to respectively identify and compensate for important aspects and unknowns that may or may not require attention. Since constraints *"intimately relate"* to design objectives (Ervin & Gross, 1987), they are therefore considered intrinsic to problem solving. Hence, constraints are seen to have the ability to provide a means of respectively expressing and capturing pertinent design information and knowledge (Frank & Wallace, 1995) that can be useful in problem structuring. Using constraints to capture knowledge relevant to design-problem structures means that such constraints may be explored further, in which successful instances may then be used to enhance the design space (Singh et al., 2007). As such, design space can be investigated by simple testing of constraints and different methods of constraint handling. Figure 3-3 (p.34) demonstrates a basic testing operation for constraints and the design space which has been based on the basic module and elements considered at the heart of the designing process according to Asimow (1962, cited by Dieter, 1991, p.3).

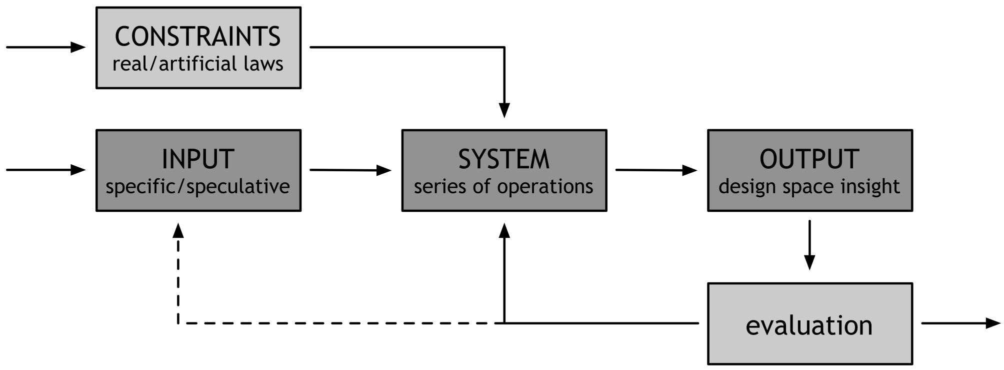

Figure 3-3: Constraints and Design Space Testing Operation.

Figure 3-3 shows the basic operation in which a set of specific or speculative variables are the 'input' to a 'system'. This system consists of a series of various operations that are essentially a representation of design space. The system and its operations are bounded by applying 'constraints' that are in the form of real or artificial laws which are declared either before or at the same stage as the inputs also are declared. The 'output' from the system then provides an insight into the design space and is 'evaluated' in order to test not only the effectiveness of the system and if designing criteria or requirements have been met, but also if the relevant constraints have been fully satisfied. The testing is then repeated according to the evaluated result until a satisfactory or preferred outcome is reached.

The elements of the testing operation seen in Figure 3-3 can in fact also be used to describe how the role of constraints are inherently relevant. This is in the context of carrying out the actions of the designing process and knowledge discovery which is based on the concept of design according to Dixon (1966, cited by Preiss, 1980, p.231).

Table 3.1 (p.35) can be used to describe the action of designing as the 'designing process' when the given elements of 'input', 'constraints', and 'output' are sufficiently available for testing and evaluation. The element of a 'system' is required as it is either entirely lacking or, is available but not necessarily complete. As such, all elements can arguably be used to describe designing as the processing and evaluation of inputs and constraints to develop a preferred solution in the form of a system structure. This viewpoint indicates the use of constraints as being significant to designing of any potential or preferred system within a design space. This table also describes the action of 'knowledge discovery' using the same elements that describe designing. When given the elements 'input', 'system', and 'output' as being available for testing and evaluation, it is 'constraints' that are required in order to complete the process that facilitates or rather makes the action of knowledge discovery. As such, this viewpoint indicates how constraints are not only important to designing process but to developing knowledge within design spaces. Overall, constraints are identified as significantly contributing to knowledge discovery. This is considered to be fundamental to developing understanding which has been identified in the previous chapter as being one of the most significant elements to designing in general.

GIVEN ELEMENTS	REQUIRED ELEMENT	RESULTING ACTION
input / constraints / output	system	designing process
input / system / output	constraints	knowledge discovery

Table 3.1: The Actions of the Designing Process and Knowledge Discovery as Described by Given and Required Elements.

As part of this section, constraints have been examined as an approach towards designing and their ability to represent design space and describe problem solving structures. This is based upon their capacity for knowledge capture and discovery . As such constraints can be tested using the simplest of testing operations such as that seen in Figure 3-3 and/or other constraint handling methods. In a similar vein to using problem structuring that faciliates understanding with respect to construction of the design space (Simon, 1973 cited by Goel & Pirolli, 1992), the next section also considers how constraints can provide a means of understanding in general design-problem solving.

Constraints as a Means of Understanding in Design-Problem Solving

The informative nature of constraints in design spaces or problem structures especially allows for knowledge to be effectively handled throughout designing process (Mullineux et al., 2005). Constraints also contribute to design rationale (Chung & Goodwin, 1998) and are used in instances of testing the feasibility of decisions made (Miguel & Prestwich, 2007) forming iterative exploration processes of constraint and/or design optimisation towards achieving a preferred outcome. However, it is noted that even when an outcome emerges, this does not necessarily mean complete design space exploration has occurred (Yan & Sawada, 2006).

The generic form of constraints as rules that must be satisfied is easy enough to be represented and simply interpreted, even in an interdisciplinary context increasingly seen in designing. Table 3.2 (p.36) shows similarly grouped constraints, some of the ways in which they might arise or act, and also how constraints with respect to facilitating knowledge might infer understanding that would be a consequence of applying constraint-based thinking, the actual constraints, and their handling thereof. Such understanding is considered to only emerge when the interaction or interconnections of constraints are investigated, for example, creating and exploring 'constraint networks with multi-directional inference' (Bowen, 1997). That is to say, networks that are highly connected nodes that are all affected by each other in various ways that propogate effects when tested with different inputs, constraints, or other specific instances.

The knowledge that leads to understanding and emerges from, or is formalised with constraints, is also significant to creativity and innovation which have both been described in the previous chapter as being strongly rooted within knowledge. With respect to constraints, this thesis strongly supports the notions that *"innovation is born from the interaction between constraint and vision"* and that *"creativity thrives best when constrained"* (Mayer, 2006). Constraints and creativity are discussed in the next section.

	RULES establish	OBJECTIVES establish	RESTRICTIONS establish / understand	DEFINITIONS understand	RELATIONSHIPS understand	SPECIFICATIONS understand / evaluate
Preiss (1980)				Define design requirements.	Support design decoupling to allow working assumptions.	Specify design work separate to demands of the user.
Gross (1985)	Establish working set of rules.		Bound variant designs.	Define context of design work.		
Baykan & Fox (1987)		Represent the overall design goals.		Define search space & represent domain knowledge.	Develop understanding of elements within the search space.	
Ervin & Gross (1987)		Are intimately linked to design objectives.		Describe the design space.	Specify design relationships.	
Bowen et al. (1990)				Describe effects design decisions have on different options.	Specify relationships that assumed values must satisfy.	
Mackworth & Freuder (1993)			Restrict which combinations of variables are acceptable.			
Frank & Wallace (1995)			Directly represent restrictions including generic standards.	Express or declare pertinent information.		
Lee et al. (1996)			Restrict & influence most decisions made.		Specify relations maintained throughout decision process.	
Bowen (1997)			Restrict values assumed by a parameter or group thereof.	Declares assignment of values to parameters.	Intentionally specify relations.	
Chung & Goodwin (1998)	Establish rules in a structured framework.		Establish impositions as a result of design requirements.			
Régin (2004)				Define domains of possible values for each variable.	Link variables with sets of combinations that are allowed.	
Mullineux et al. (2005)	Establish working set of rules.					Derive from the specification.
Stokes & Fisher (2005)			Preclude solution searching.	Promote search for novelty.		
Hicks et al. (2006)	Establish working set of rules.	Translate into objectives.		Declare what is to be achieved, not how it is to be achieved.	Demonstrate relationships between parameters.	
Singh et al. (2006)			Impose limits on what is possible to drive the design process.			
Yan & Sawada (2006)			Translate as restrictions.	Declare direction of information flow but does not specify the information.		
Miguel & Prestwich (2007)				Make characterisations on sets of decision variables.		Specify feasible or infeasible decisions for captured states.
Buscemi & Montanari (2008)			Specify enforceable relationships, not procedures to do so.	Declare solution properties, not operations to find them.		
Onarheim & Wiltschnig (2010)			Frame & limit design space through requirements.	Define polarities of the design-problem space.		

Table 3.2: Actions of Constraints Towards Facilitating Understanding in Design-Problem Solving.

Constraints as a Means of Understanding Towards Optimisation in Designing

Designing is most commonly a process of optimisation which itself may be presented as a problem that fundamentally aims *"to arrive at the best possible decision in any given set of circumstances"* (Walsh, 1975, p.1). It yields preferred or rather optimal solutions that are a 'best compromise' of the circumstances which are known to take various forms. Most simply, design optimisation can be viewed as being largely governed by those related to the variables of objectives and constraints.

For design-problem solving, optimisation by achieving a single objective is rarely the case. In reality, practitioners are instead more likely to be handling problems that have multiple objectives. In mathematics, an optimisation problem can be described as an objective function which is to be either maximised or minimised. This is with specifically assigned input variables in order to solve the problem which is subject to given constraints, and at the same time. This is known generally as a constrained optimisation problem (Walsh, 1975).

As noted earlier within this chapter, mathematical approaches are often applied towards such problems and there is much interest in the research of multiple-objective optimisation problems. Specifically, when looking at scenarios of multiple objectives, there are different approaches towards such problem solving. For example, either reducing the many objectives down to one that is more simplified or, by placing the focus upon one objective that is of specific interest whilst the others are considered as constraints (Goel et al., 2007). Using objectives and constraints interchangeably is supported in this thesis within the context of constraint handling and also supports the idea that approaches towards designing will always encounter constraints. Hence, they are in fact all constraint-based, especially when applying constraint-based thinking and when constraints are thought of in the right way.

3.3 Constraints and Creativity

Historically, creativity has negative correlations when associated with the notion and perceptions of constraints (Amabile, 1996). However, it is strongly believed within this thesis that constraints are highly functional and in fact effectively contribute towards creativity in designing process. This section begins by considering the role of constraints towards creativity and the creative process in the context of, and with respect to the closely related designing process. It then explores how constraints can either preclude or promote creative and/or design spaces, and in doing so, facilitate understanding towards effective designing.

3.3.1 The Role of Constraints Towards Creativity and Creative Process in Designing

Creativity as creative-problem solving, designing as design-problem solving, and cognitive process, are considered as all being closely related. Knowledge and understanding is especially significant to all of these. This is to the extent that constraints, creativity, designing, and cognition are inextricably linked with respect to knowledge and its respective discovery in the handling of the constraints.

In designing, constraints can be used interchangeably with design requirements (Onarheim & Wiltschnig, 2010) and are said to enable creativity by balancing designing with appropriate responses. In addition, the direct handling of constraints arguably facilitates the more timely emergence of knowledge that may have otherwise been overlooked until further along the process.

When given a design problem with a vision for what is to be achieved, the interaction between this and specific constraints can lead to the notion of how innovation might occur with respect to the use of constraints themselves. It relates to the view of Mayer (2006) in which innovation is considered as the result of the interaction between constraints and a vision that is to be achieved and/or realised.

Figure 3-4 shows a flowchart of how constraints and designing might occur together. It demonstrates that when given a design problem, constraints and objectives that are indeed interchangeable, are co-defined at the beginning of the process. Once these constraints and objectives are formally declared and/or identified, constraints are respectively handled and resolved. As part of this process, they are reviewed to evaluate if the defined objectives have been met, or if the defined constraints have been satisfied. Finally, constraints are redefined or modified until an acceptable or preferred outcome for detail design is achieved. In optimisation where there is no acceptable solution a 'best compromise' is settled upon as the preference that is carried forward.

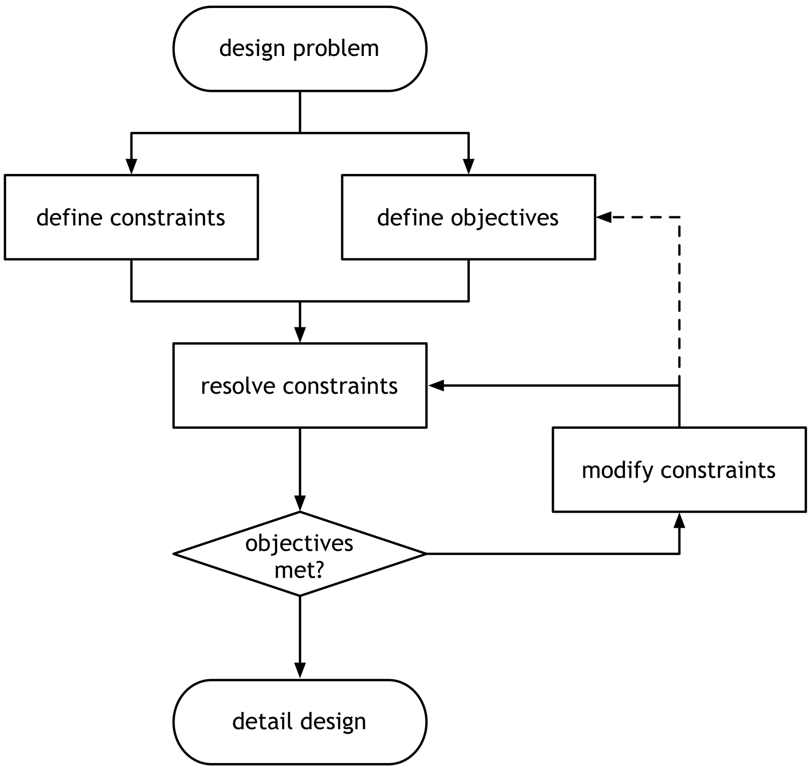

Figure 3-4: Flowchart of Constraints and Objectives and their Interaction in Designing.

For constraints that arise, other than those that extend from physical and natural laws, it is the practitioner's decisions and/or design rationale that ultimately decides upon the features of different constraints, how they are relevant, and how they should be handled within the context of the design problem. Such constraints are therefore deemed to be inherently subjective, even if objectively inferred. Furthermore, there is to some degree, a level of creativity that can be found and occurs in directly handling the constraints themselves (Stokes, 2007) which is also dependent upon the practitioner.

As constraints naturally arise in design-problem solving, creativity also naturally arises as a result of handling contraints, of which there are many approaches. When considering how constraints might be handled with respect to exploring design spaces and problem structures, it is pertinent to observe the perspective that constraints *"come in pairs"* and will either *"preclude or promote"* (Stokes & Fisher, 2005). Specifically in terms of the design space, constraints will be either *"limiting or opening"* (Onarheim & Wiltschnig, 2010). That is to say, the overall design space will either decrease or increase depending on the influence of constraints and how they are used to structure the design problem. How constraints might preclude and promote creativity in designing is examined in the following sections.

3.3.2 Precluding Creativity with Constraints

In the instance where constraints preclude creativity, constraints are used to predominantly limit the design space and can even prohibit acceptable outcomes. Solutions available are generally low in variability. This section discusses how constraints preclude creativity and designing which are both closely related. The response to negotiating such constraints by promoting creativity is then described in the next section.

Limiting Creativity with Constraints

With respect to 'limiting' the creative process, when especially rigid or rather hard constraints are imposed, the design problem becomes over-constrained. The design space is limited to the extent that a satisfactory outcome may be increasingly difficult to achieve.

Constraints that limit, although they may restrict and preclude creative and/or design process are still fundamentally necessary in order to structure problems and explore design spaces so that they are well-defined and therefore solvable.

Prohibiting Creativity with Constraints

With respect to 'prohibiting' the creative process, when constraints are excessively imposed, together they become so restrictive that the problem is over-constrained and an acceptable outcome is prohibited, or impossible to achieve. In contrast, if all imposing constraints are themselves prohibited, the design problem would then become excessively under-constrained and an acceptable outcome is equally prohibited.

In some cases, when constraints are conflicting, prohibiting one or more imposing constraints can be useful as a line of inquiry so that an acceptable outcome is then only limited, as opposed to being entirely prohibited.

3.3.3 Promoting Creative Designing with Constraints

In the instance where constraints promote creativity, they are used to predominantly direct problem structuring and either frame or open up the design space so that an acceptable outcome is achievable. Solutions available are generally high in variability. This section discusses how constraints can promote creativity and designing which are both closely related. It presents framing and opening as the response to counteract constraints that preclude creativtity, as described in the previous section.

Framing Creativity with Constraints

With respect to 'framing' the creative process, constraints are imposed so that the problem is well-structured and hence the design space is also well-defined. As a result, constraints can more immediately direct designing with respect to specific knowledge that might emerge or is required in order to faciliate understanding. Framing design spaces with constraints can also direct a search or specific lines of inquiry which are consequently creative by being uniquely appropriate for a particular design problem. Constraints that frame creative and/or design process are generally less rigid or rather soft constraints that are applied in order to direct and promote creativity. They are closely related to constraints that limit creativity as they are more likely to be rigid or hard and cannot be violated, therefore precluding more than they promote.

Opening Creativity with Constraints

With respect to 'opening' the creative process, when constraints are either relaxed, replaced, and/or removed, the design problem becomes under-constrained. By doing so, there are fewer restrictions and an increased capability to explore problem structures and the design space. This is with respect to design alternatives that might not have otherwise been possible and hence, exploration in general can allow for a more novel response. Opening constraints is a response to counteract instances that might have been previously over-constrained and where no acceptable outcome was achievable. This may involve translating hard constraints to soft constraints and therefore allow violations for the sake of 'not-so-bad' solutions. In contrast, when constraints are entirely removed, there will again be no acceptable outcome. Constraints are indeed inherent and absolutely necessary for results to be achieved.

3.4 Chapter Conclusions

In this chapter, since constraints always arise, constraint-based thinking has been considered in the context of design-problem solving. It has identified constraints as being inextricably linked to the elements of creativity, designing, and cognitive process, and have proved useful in structuring design problems and investigating design space. It has further been concluded that constraints are highly functional in precluding or promoting creativity and designing. They are fundamental to knowledge discovery, and as a means of understanding, they are especially significant towards optimisation in designing of all kinds.

It appears that there is an opportunity to apply constraints as a mindset and philosophy towards design-problem solving.

The next chapter considers sustainable development and the impact of sustainability towards sustainable design, and as a design-based example that is highly interdisciplinary.

Chapter 4

From Sustainability and Sustainable Development to Sustainable Design

"Sustainable development meets the needs of the present generation without compromising the ability of future generations to meet their own needs" - The Brundtland Report, WCED.

In recent times, the concerns regarding 'sustainability' and 'sustainable development' have arguably shifted the patterns in working that influence the principles of designing. Overall, the desired effect is aimed at positively supporting achievements against climate change. This chapter aims to explore sustainable development as an example of interdisciplinary design and the influences of sustainability. It begins examining what sustainability is, what it means to sustainable development, the integrated elements that are intrinsically involved, and how sustainability is measured. Finally, this chapter considers how sustainable development affects general designing approach and the interdisciplinary nature of this.

4.1 Understanding Sustainability Towards the Practice of Sustainable Development

Sustainability and sustainable development are fundamentally interdisciplinary in nature. This section makes the distinction between sustainability and sustainable development as being different and then examines the integrated elements relevant to both.

4.1.1 A Perspective of Sustainability and Sustainable Development

The ideals of sustainability extend from a three-hundred year old notion in sustainable yield of timber supplies required for the Saxony mining industry. It was introduced by mine inspector Carlowitz (1713) in his book, *"Sylvicultura Oeconomica"* - Silviculture and Economics. Today, sustainability and sustainable development is an increasingly growing concern for many including economists, environmentalists and humanitarians alike.

SUSTAINABLE DEVELOPMENT / SUSTAINABILITY MODEL	PEOPLE	PLANET	PROFIT	POLICY
Sustainable Economic Development (Barbier, 1987)	social system	biological & resource system	economic system	
Capital Stocks of Sustainable Development (World Bank, 1994)	social capital	environmental capital	economic capital	
Triple Bottom Line / Three Pillars (Elkington, 1994)	people	planet	profile	
Prism of Sustainable Development (Spangenberg & Bennoit, 1998)	human capital / social	natural capital / environmental	man-made capital / economic	social capital / institutional
MAIN Prism of Sustainable Development (Kain, 2000)	mind	nature	artefact	institution
Sustainability Assessment Venn Diagram (Hammond, 2004)	society	ecology & thermodynamics	economics & technology	

Table 4.1: Models of Sustainability and Sustainable Development.

The concept of sustainable development was politically defined in 1987 by the World Commission on Environment and Development. The Brundtland report, officially entitled *"Our Common Future"*, sought to integrate the issues and consequences of environmental damage whilst considering economic and social development. The report led by Chairman Gro Harlem Brundtland provides the most commonly quoted definition as *"meeting the needs of the present generation without compromising the ability of future generations to meet their own needs"* (WCED, 1987). It is also arguably, the most widely accepted definition that is available.

The Distinction Between Sustainability and Sustainable Development

The term sustainable development and sustainability are not equivalent but they are inextricably linked. As stressed separately by both Parkin and Porritt (2000 cited by Eaton et al., 2007), sustainable development is merely the process or action towards the desired outcome of sustainability. The desired outcome of which, is expressed as requirements or objectives that are to be achieved. Models attributed to both sustainable development and sustainability exist but in most circumstances demonstrate the integration of three elements known as *"the triple bottom line"*. It is perhaps the most common means of expressing such elements and even a means of describing the underlying principles of sustainability itself. A number of existing models and their assoicated elements are discussed in the next section.

Common Integrated Elements of Sustainability and Sustainable Development

Originally in response to the concerns surrounding sustainable development and under the influence of 'corporate and social responsibility', the triple bottom line was introduced as a turn of phrase in the nineties. This was the result of an effort by Elkington and his counterparts at the company SustainAbility (Elkington, 2004). The 3P formulation of *"people, planet and profits"*, also known as the 'three pillars', was also developed around the same time. It is synonymous with many associations made towards sustainable development and/or sustainability. Table 4.1 (above) describes a number of models that are compared against the elements most commonly recognised as the triple bottom line.

PEOPLE human capital / mind	PLANET natural capital / nature
Worldview, skills, knowledge, experience, and the ability of the people as a labour force to increase value and quality of life.	Environmental and natural resources, renewable and non-renewable stocks, biodiversity, clean air and healthy water.
PROFIT **man-made capital / artefact**	**POLICY** **societal capital / institution**
Financial capital, man-made assets such as buildings or roads and man-made materials enabling further production of assets.	Societal structures such as healthcare or planning systems that form a collective value of connections in a social network.

Table 4.2: Descriptions of Sustainability and Sustainable Development Capital Relevant to the Four Fundamental Elements.

Described visually or otherwise, the sustainability and sustainable development models presented in Table 4.1 differ in comparison from the designing models previously described in Chapter 2. For the most part, they do not demonstrate a strategic process but rather the singular elements that need to be considered for something to be deemed 'sustainable'. As such, these elements have even emerged as providing measures of sustainability in various forms. With respect to the models described, and to mainly account for the two prism models, the element of 'policy' has been added referring to those set within a political or organisational context. Policy in the form of legislation and statutory requirements would be significant here, and is indeed one of the influences that drives sustainability and hence, contributes to a new perspective for this thesis by adding the element of 'policy' to the existing triple bottom line.

A New Perspective to Sustainability and Sustainable Development

Sustainable development in terms of people, planet, profit and policy is considered in this thesis to be a more modern and realistic interpretation. Some of the models described in table 4.1 present sustainable development as different types of capital. These are put into context in table 4.2 with respect to what this thesis now considers as the four fundamental elements of sustainability and sustainable development and the new perspective towards it.

From the descriptions and models provided, it can be seen that the process of sustainable development is the integration of different elements. The use of 'venn diagrams' in which the intesection of all elements represents the measure of sustainability achieved, is common practice from as early on as 1987. Barbier (1987) represented his model for sustainable economic development as a venn diagram of three different systems. The three pillars and various sustainability assessments are also commonly represented as so. Figure 4-1 (p.45) demonstrates the intersection of people, planet, profit and policy as the nominal level of sustainability achieved. In the context of the new perspective, any process must include the mutual consideration and integration of these four elements which also provide simple measures for sustainable development in general, and are examined in the next section.

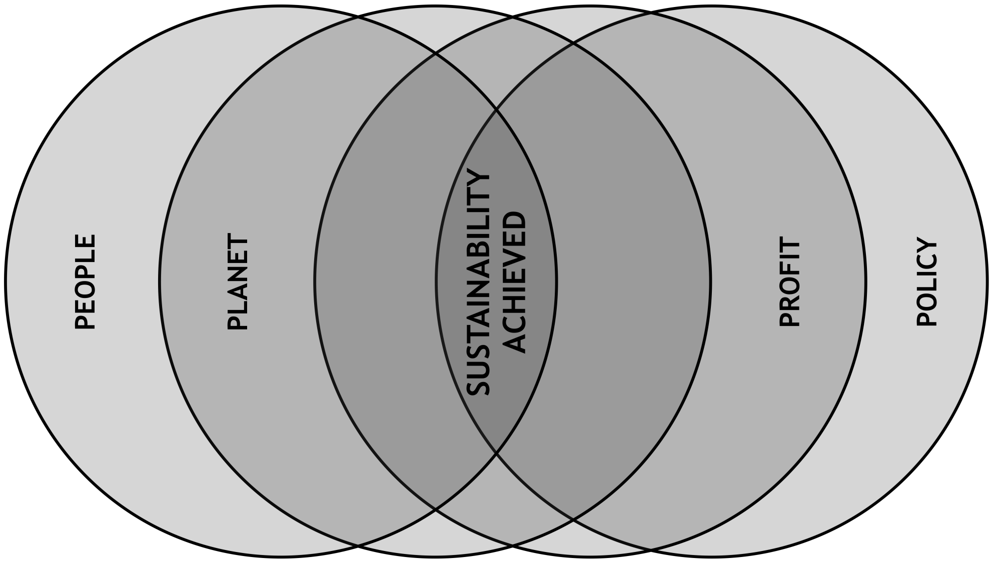

Figure 4-1: Sustainability Achieved at the Intersection of People, Planet, Profit and Policy.

4.2 Impact Assessments in Measuring Sustainability and Sustainable Development

Early drivers that have contributed to current processes of sustainable development are strongly rooted in the environmental concerns at the time. This is to the extent that they have born some supporting fields which includes ‘ecodesign’. They have also led to the development of tools that contribute towards current practice and some are now common place within sustainable development. These tools are based on providing assessments that are ‘snapshots’ of scenarios and are simply a measure of impact. This section looks at a sample of prominent measurements as methodologies that attempt to provide different means of impact assessment. The original motivation for all are considered to be extended from a background of environmental concern.

4.2.1 Life Cycle Assessment

Life cycle assessment (LCA) provides a supporting tool of sustainable development. It is an exemplary methodology that has primarily evolved from two key sources. These are the Resource and Environmental Profile Analysis (REPA) of the 1960s and the Society of Environmental Toxicology and Chemistry (SETAC) Framework of the 1990s. Now regulated by the ‘International Organization for Standardization’ (ISO) and the 14000 series, LCA is based on four foundation elements originally specified by SETAC. They are goal definition, inventory analysis, impact assessment and improvement and are applied over a ‘cradle-to-grave’ timeframe of the product, process or system. The respective sequence of elements collectively form the LCA process. However, as basic actions, they also reflect aspects of general design phases such as establish, understand, generate and evaluate.

4.2.2 IPAT: The Sustainability Equation

Impact assessment is strongly favoured in sustainable development, especially that of environmental impact. Originally devised to determine environmental disruption by Holdren and Ehrlich (1970 cited by Hammond, 2004), the IPAT equation is defined as an acronym of its terms. The equation simply considers the three elements of population in millions, affluence through gross domestic product (GDP) per capita and technology as environmental damage per unit of consumption and resource productivity. The equation is seen directly below.

$$(Environmental)\ Impact\ (I)\ =\ Population\ (P)\ \times\ Affluence\ (A)\ \times\ Technology\ (T)$$

The IPAT equation, over the years, has become known as the *"sustainability equation"*. Although, as such a simple equation it is considered to be easily manipulated. The dominance of each term, without careful consideration or moderating, may extensively alter the overall result. Interestingly, the equation has been adapted (Hammond, 2004) with the original measure of environmental impact being directly replaced for energy consumption and used for making predictions or forecasts of the latter. The equation of which is as follows.

$$Energy\ Consumption\ =\ Population\ \times\ GDP\ per\ capita\ \times\ Energy\ Intensity$$

4.2.3 Footprinting

Assessments that make use of performance indicators form a strong foundation for which many sustainability assessments are based upon. The need for such indicators provides measurable and quantitative but also objective targets for sustainable development (Spangenberg & Bonniot, 1998). Footprinting provides indicators and metrics that are the result of static assessments, but they still have merit as standalone values. However, when comparing as benchmark footprints against those of different scenarios or designed solution strategies, this forms a process that makes it possible to make comparisons and mark any improvements in an iterative manner.

For footprinting, the results are always considered to be somewhat subjective. This is despite their basis of measurable and quantitative inputs. This is, for the most part, due to the judgement calls of the practitioners involved. For example, the assigned weighting of different impacts of various measures, what is considered to be within the boundaries of the problem context, and also the methods of data collection and processing. Indicators such as the footprint and their associated methods are an example of an effort that has been made in order to provide the provisions for universal, measurable, and quantitative targets of performance. The most common of which are discussed here. They are carbon, environmental, and water footprinting.

Carbon Footprinting

Carbon footprinting although so-called is not strictly as its name implies. These footprints are in fact a measure of greenhouse gas emissions that can be directly and indirectly attributed to an individual, product, process, or system.

The gases included are carbon dioxide (CO_2), nitrogen oxide (N_2O) and methane (CH_4). They are converted using a factor of 'global warming potential' (GWP), over a period of one-hundred years, into what is expressed as 'carbon equivalents'. The total weight in tonnes of carbon equivalent (tCO_2e) provides the measure of carbon footprint.

Carbon footprints have become somewhat of a climate change metric. It is a simple metaphor for impact. However, there is an absence for a universally established methodology in how to capture, measure and quantify a carbon footprint. There also exists disagreement in the definition of carbon footprint itself (Weidman & Minx, 2007). Regardless of such disagreements, current processes for calculating carbon footprints, also known as carbon accounting, involves the collection of highly detailed data and a series of data intensive calculations. Although, far from it, progress has and continues to be made towards an established methodology. This is demonstrated with the Publicly Available Specification, PAS 2050 (2008), the Greenhouse Gas (GHG) Protocol's Product Standard (2011) and the ISO 14067 (2012).

Environmental Footprinting

The theoretical framework behind environmental footprinting was founded by Rees (1992) and Wackernagel (1994) and provides a metric for the measure of how human lifestyle, and, demand and consumption of resources impacts upon the 'carrying capacity' of the earth. Synonymously known as ecological footprints, it also uses carbon footprinting as an element of its assessment and one of its measures of reporting.

Environmental footprints account for the natural resources and waste of a specific individual, population and or economy and calculates the corresponding area of land required to produce and handle such resource demand and waste generation as a measure of impact in terms of global hectares (gha). This is converted from the standard hectare unit (ha) using the relevant equivalence factors. In the UK, the total footprint is 4.71gha/capita, meaning that if the world consumed as the UK does, 2.65 planets would be required to provide the resources consumed and to absorb the waste that is generated (GFN, 2012).

Water Footprinting

As a relatively new means of assessment in terms of sustainable development and an indicator of sustainability, water footprints have been introduced within the last decade. They are simply a measure of human demand and consumption on the earth's freshwater resources.

Defined as the total volume (litres) of freshwater used to produce the goods and services consumed by an individual or community (Hoekstra, 2009), water footprints illustrate the links between human consumption and water use, but also between global trade and water resource management. They demonstrate a 'primary resource perspective' that brings to light and demonstrates that a consumer and global aspect should be added in consideration of good governance.

4.3 The Influence of Sustainability and Sustainable Development in Shifting the Principles of Designing

In the previous sections, a new perspective of the underlying principles and methods of measuring sustainability and sustainable development were explored. This section considers the highly interdisciplinary nature and the consequent influences of sustainability and sustainable development on the designing process.

4.3.1 Shifting Principles in Designing

Despite the existing attempts of descriptions and models as presented in Section 4.1, it is still difficult to define sustainable development as a process in 'a way that is actionable' (Lauder, 2012). This is also considered in some cases to be true of engineering design and designing in general. The difference between the two is that over the years, established patterns of working and process set by precedence has significantly furthered the field of engineering design.

Sustainable development is still in its early days of being established. This is much like its partner discipline of 'sustainability science' which is very much a product of the 21^{st} Century. Continued efforts within the field attempt to simply master a comprehensive strategy that *"recognizes the complexity of the issues and the tradeoffs involved"* (Lauder, 2012, p.1).

The importance of achieving sustainability in current times is so great that the effort to change has seen governments and institutions respond to the issues at hand with increasing vigour. The process, sustainable development, by its very nature in definition, is a holistic practice that brings together many technical and specialist fields. Therefore, it is now more important than ever to have an understanding and appreciation of different fields that contribute to a sustainable outcome. In this way, sustainable development has arguably helped to shift the patterns of working to be more integrated than they have ever been before.

4.3.2 Encouraging the Shift Towards Interdisciplinary Designing

Design practice that responds to the influence of sustainable development is deemed within this thesis as closely related to 'sustainable design'. By its own nature, such design has a very wide scope of inclusion and hence increasingly involves many different fields. Whilst it is considered to be a multidisciplinary practice, with collaborative efforts of different 'discipline specialists' working alongside each other, this is simply no longer sufficient.

Sustainable development and therefore sustainable design demands the integrated efforts of its practitioners. For an interdisciplinary practice, the integration of distinct disciplines deepens knowledge and increases application beyond the scope of one discipline alone. Thus contributing to improved practice and new knowledge acquisition for a field such as sustainability. However, a consequence is the challenge of increased complexity, knowledge gaps across disciplines and an emergence of conflicts between.

The challenge of integration can be found at the most basic level. Even the differing use of simple language, in terms of discipline-specific terminology or technical jargon, can hinder communication (Goel, 1995). This is between the practitioners as well as across different disciplines. In many ways, current methods within design are often overly discipline specific. The extent of which somewhat hinders integration of shared knowledge as a result of the differing approaches from the different disciplines that exist. In addition, they do not facilitate integrated design or a respective methodology. Hence, any form of integrative approach has the opportunity to greatly advance design with integration across different disciplines and between discipline specialists.

Although sustainable development is not solely responsible, it has certainly been a catalyst for an integrated effort towards integration across different disciplines and encouraged a shift in design practice. This has largely been driven by the holistic approaches that are demanded. Practitioners are therefore working within their own disciplines but increasingly required to offer expertise beyond the scope of their own specialist knowledge. An example of this can be seen within the 'built environment' in which sustainable development has had a great influence. The impact of considering how to meet sustainability objectives have also compounded issues of complexity that variously arise.

4.4 Chapter Conclusions

In this chapter, sustainability has been described as the integrated elements of people, planet, profit, and now in this thesis, policy. It has also been concluded that sustainable development is inherently interdisciplinary, and there has been development of impact assessment tools to support this. Furthermore, it is noted that the interdisciplinary influence of sustainability has led a shift in principles of designing to also be increasingly interdisciplinary, and to which issues of complexity invariably arise.

Since sustainability is an emerging issue, there is relatively little research that has been done to tie it into general designing processes. If this is done, it makes design-problem solving increasingly interdisciplinary, and therefore requires new techniques to be able to handle this. This is the focus of this thesis.

The next chapter further considers the principles of sustainability and sustainable development in the context of the built environment and more closely considers the issues of highly interdisciplinary design that is also affected by complexity.

Chapter 5

The Built Environment

"We shape our buildings, thereafter they shape us" - Sir Winston Churchill.

The built environment involves many different disciplines and is heavily influenced by the issues of sustainability, and with much interest towards making contributions. This chapter aims to explore the built environment as a design-based field which is highly interdisciplinary, but also complex. It begins by examining the built environment, the breadth of those involved and its connection to sustainability and sustainable development. It then considers masterplanning as an integrated service provision for developers within the UK planning system and a system that aims to maintain the integrity of the built environment that is subject to legislation and statutory regulations. Finally, this chapter examines current methods and some of the supporting tools available for such a practice.

5.1 Understanding the Built Environment

The interdisciplinary nature of the built environment is as multifaceted as designing. This section firstly considers the scope of the built environment and who can influence and/or are influenced by this so-called field. It considers the connection to sustainability and sustainable development and goes on to consider how complexities arise in practice.

5.1.1 A Perspective of the Built Environment

The built environment is somewhat of a blanket term that broadly describes man-made spaces created and thereafter, inhabited by people on a day-to-day basis (Roof & Oleru, 2008). It includes formal elements such as those of urban design, land use, transportation systems and patterns of human activity (Handy et al., 2002).

Not strictly an established profession or an academic discipline, its interdisciplinary and multifaceted nature involves actions such as those of 'designing, planning, management, and appraisal' (International Federation of Landscape Architects, 2003 cited by Bartuska, 2007, p.4). In formal terms, the built environment most appropriately falls under the remit of the architectural, engineering, and construction (AEC) industries.

ADAPT science & technology	FUNCTION economy & society	IMPACT ecology & environment
The expertise and knowledge applied for the benefit of better living and the artefacts and/or systems that are created.	The development, government and maintainance of practices, policies and infrastructure for everyday living.	The expense of changes caused by day-to-day living and the consequent affect on the natural world and all its living inhabitants.

Table 5.1: The Fundamental Elements of the Built Environment.

Bartuska (2007) generally defines the built environment as being a holistic concept of human activity. It is *"everything humanly made, arranged or maintained"* that fulfils human purposes and mediates and/or results in a change to the overall context of the environment. Quite simply, the built environment concerns the 'political and societal culture, artificial products and spaces, and the systems that are built and developed'.

In this thesis, the built environment in interpreted as consisting of three fundamental elements that are altogether summarised in table 5.1. The first element is with respect to how humans 'adapt' themselves and their physical environment using science and technology for advancing general quality of life. The second element considers how humans 'function' within this physical environment, and specifically with respect to the policy and/or practices that are both respectively governed under the influence of policy developers, regulating bodies, and/or legislation and stautory requirements. The third and final element is concerned with how changes to the physical environment 'impact' upon the natural world, its living creatures and aspects such as climate change.

5.1.2 The Theorists of the Built Environment

It is in no doubt that the built environment is strongly under the influence of man-made outcomes and its many inhabitants of various natures. However, those who are most likely to shape the built environment or those who need to be mindful are considered theorists, and are very similar to design theorists of design thinking. Bartuska (2007, p.3) comments that *"we all build and therefore make important contributions to the built environment"*. Consequently, this affects both our means of living and the natural world in which we live. The theorists, as those examining theories within this field, must therefore acknowledge that although the environment may naturally be most significant, as are the influences of governing practices, the culture and living within society. Therefore, those that may positively benefit from understanding the theories behind either individual elements or a more holistic overview of the built environment can be grouped into the following categories or perspectives.

- **Practitioners** - those who practice designing/planning in the built environment.
- **Instructors** - those who teach or provide education in the built environment.
- **Researchers** - those who perform research in the built environment.
- **Governors** - those with authority in actions, policy and procedure.

Much like the design theorists, there are 'practitioners', 'instructors', and 'researchers'. However, in line with the new perspective of sustainability from the previous chapter, and as the integrated elements of 'people, planet, profit, and policy', 'governors' are also included as a built environment theorist. They are, as described, in an authoritative position, and the governing bodies, institutions, organisations and policy makers that guide and govern the processes. This includes processes that are currently applied by practitioners, but also those that might be in development. In this regard and in comparison to designing and engineering design, work in the built environment is as much a technical process as one very much subjected to strong-arm political pressures that often weigh heavily within the field.

5.1.3 The Importance of the Built Environment and its Connection to Sustainability and Sustainable Development

The built environment covers an extensive range of varying fields or domain disciplines. Considering this, one of the overarching priorities and drivers for the inclusive disciplines is the influence of sustainability and sustainable development. Chapter 4, has previously discussed the shift in general designing principles that are influenced by sustainability and sustainable development. This is applicable for many but none more so than those involved within the built environment.

Under legal obligation, the UK has committed to reducing its greenhouse gas emissions and to achieve an 80% reduction against the baseline figures of 1990 (HMSO, 2008). The scope of the built environment means that it is *"inextricably linked"* with programmes for carbon reduction (IGT, 2010, p.15). Its operation alone and the use of buildings accounts for approximately 80% of CO_2 emissions (IGT, 2010, p.23).

With regards to this legal commitment and the large scope of those involved, it is considered within this thesis that there is great potential for making a contribution in knowledge. This is towards improved and better working practice within the sector. Importance of the built environment largely lies in its impact on CO_2 emissions and the effects on climate change. This consequently has a significant importance and bearing on the way in which we live and how we may live in the future. As a result, many working directly within the scope of the built environment are responding to the demands of their field against the needs of sustainable development with increasing vigour.

5.1.4 Complexity and the Influence of Interdisciplinarity in the Built Environment

The interdisciplinary nature of the built environment and sustainable development means that they are not just closely related, but inextricably linked. The integrated elements of sustainable development as 'people, planet, profit, and policy' are mutually influential to the fundamental elements of the built environment, as described in Table 5.1 (p.51). To this extent, those elements which are involved overall and also impacted upon, are in fact one and the same. In addition, standard objectives such as the Climate Change Act 2008 (HMSO, 2008) and impact metrics such as carbon footprint simply provide unifying targets, creating a common goal.

PEOPLE	PRACTICE	PRECEDENCE
'Developing' a relationship of mutual understanding. Bringing together and integrating the ways of thinking and working for a wide breadth of people from different backgrounds and with different objectives.	'Negotiating' the vast range of regulation, existing and emergent approaches, methodologies and tools. In addition, responding to shifting terminology and competing technologies that are constantly evolving.	Driving innovation by 'overcoming' the old schools of thought and established methods of working by building upon invested resources. Practising better goal seeking methods over immediately meeting client demands.

Table 5.2: Contributing Factors of Complexity Towards the Built Environment.

In response to these common goals, there are many built environment theorists attempting to search for supportive and improved methods of practice. By no means an exhaustive list, the built environment falls under the remit of academics, the government, independent advisory bodies, industrial practitioners, non-governmental organisations (NGOs), special interest groups (SIGs), and local to national authorities. The emergence of sustainable design however, is seen in this thesis as being a natural progression, most simply towards better design. It is a practice that is discerning of all those who might be involved, in order to reach common goals and satisfy shared interests.

Bringing together such an extensive range of inclusive disciplines does not come without any difficulty. Despite holding similar and shared objectives, the disciplines involved must negotiate their respective processes with each other. For the disciplines considered inclusive, within the scope of sustainable design and the built environment, the means of integrating such disciplines presents several complexities that will naturally arise.

For sustainable development, in attempting to address the issues of sustainability and mitigate the effects of climate change, the route most preferred and encouraged by legal obligation, is one of 'carbon reduction'. Using carbon footprinting, as described in the previous chapter and, as an approach in support of achieving this, is not without complications. Although it may currently be employed as a common metric, as a standardised process, it is still considered to be in development which is also indicative of the emergence of processes within the scope of supporting sustainable development.

Consolidating these processes across the different fields and disciplines involved requires integration 'across and between'. Above all else, it is the multiple disciplines involved that are required to operate in an interdisciplinary way that significantly causes complexities to arise.

The factors contributing to the complexities within the built environment as a result of interdisciplinary practice, inherently emerge from managing the interconnections and attempting to achieve a balance in the relationships of people involved. Complexities also arise in negotiating current and emergent or developing practices and overcoming precedence in order to achieve innovation. Such factors are described by the elements of 'people', 'practice', and 'precedence', and in table 5.2.

With respect to the contributing factors of complexity, as described in Table 5.2 and also outlined in the 'Low Carbon and Construction' report by the Innovation and Growth Team (IGT, 2010), complexity arises when developing the functional relationships of mutual understanding in achieving sustainability goals. This is not a simple task and requires 'people' to align their objectives and work together on consistent processes that require constant compromise for all to be in agreement.

As part of the interdisciplinary 'practice' in the built environment, complexities arise as those actively involved must negotiate a bombardment of existing and emergent approaches, methodologies, and tools. These are also regulated by rules of practice such as legislation and statutory requirements. At the same time, those involved must adapt to changes in terminology and constant advances within competing technologies. They must also manage the expanding facets of explicit, tacit and encultured knowledge, previously described in Chapter 2, within a setting that applies to built environment and designing theorists.

Finally, complexities are involved when attempting to overcome the 'precedence' set by firmly established practices, fixed ways of thinking and any investment with respect to resources. However, perhaps the most overwhelming precedence to be overcome is the habitual immediacy of meeting client demands. Using goal seeking methods to reach what the practitioners of sustainable development perceive as optimal, rather than that which the client has demanded, brings added difficulty alongside the general complexities of precedence.

5.2 Masterplanning and the Built Environment

The practice of masterplanning makes significant contributions to the built environment and this section explores it as an example that is both complex and interdisciplinary. It begins by introducing the so-called practice, how this relates to the Royal Insititute of British Achitects (RIBA) and their latest 'Plan of Work' model, and briefly compares its stages to the phases of design-problem solving. This section also considers the relevant statutory obligations and then explores and emphasises the numerous professionals that might be involved through their technical and/or resource streams. It finishes by examining some of the most significant supporting tools available.

5.2.1 A Perspective of What Masterplanning is

Masterplanning is interpreted in this thesis as a design-based activity that provides an 'integrated service provision' for the entire programme of activities in projects concerning the built environment which are most commonly based on spatial and strategic objectives. These are for projects of development or regeneration and include those that involve a significant scope of change. For example, a strategy of redevelopment for existing towns, development of a new settlement and, a specific site or event development such as the London 2012 Olympic Park. The integrated provisions include the detailing of a design brief, the necessary prepartory work, concept and detailed design, all the way through to supporting pre-construction and construction until finally in use. This is in line the stages relevant to the Plan of Work officiated by The Royal Institute of British Architects (RIBA).

RIBA's Plan of Work Stages, its Response to the Influence of Sustainability, and a Comparison to Design-Problem Solving Phases

RIBA first developed its 'Plan of Work' in 1963 and the associated 'work stages' within the model form a framework synonymous across the architectural, engineering, and construction industries. In the same way that Pahl & Beitz has influenced engineering design, RIBA's Plan of Work has become a definitive model holding significant influence for the professionals of the built environment and their practice thereof.

In response to an increasingly integrated practice and the influence of sustainability, RIBA reviewed its model in 2013 in order to ensure the changing 'ways of working' were aligned for the range of practitioners involved and that the model was *"fit for purpose for the next generation"* (RIBA, 2012). This in part, further demonstrates sustainability's influence in shifting patterns of designing and/or patterns of working that have been previously firmly established. The eight work stages of RIBA's current plan of work are shown in Figure 5-1.

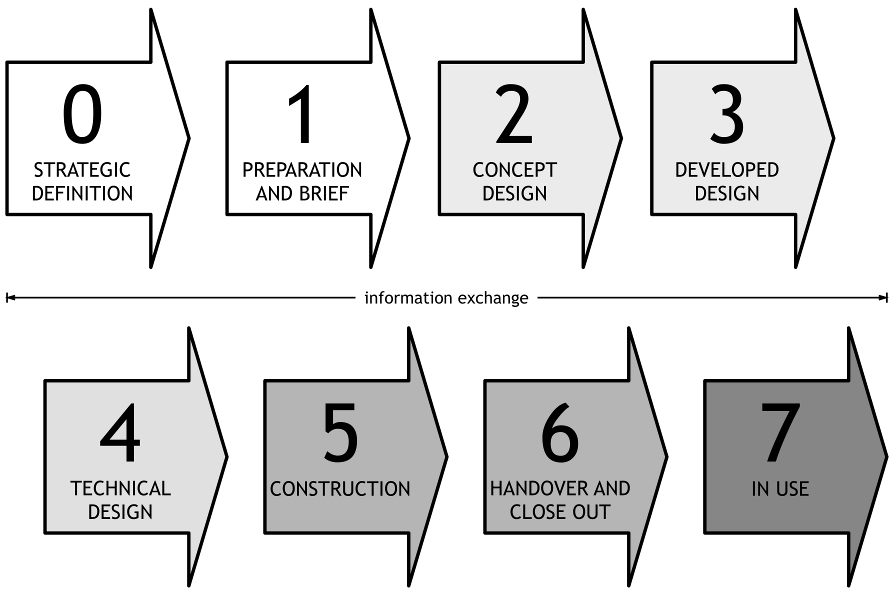

Figure 5-1: RIBA's Plan of Work 2013

In reality, for each of the work stages in RIBA's Plan of Work, there are associated tasks at varying levels. However, Figure 5-1 only offers the numbered description. When considering the real actions of each work stage in comparison to the phases of design-problem solving, work stages zero and one are directly comparable to the phases 'establish' and 'plan' respectively. Work stages two, three, and four are all comparable to both the phases 'generate' and 'evaluate', and work stages five and six are respectively and predominantly comparable to the 'communicate' phase. As a result of the emphasis placed upon 'information exchange' throughout all work stages of RIBA's model, every stage is considered relevant to the 'understand' action from the complete set of design-problem solving phases.

The Statutory Obligations of Masterplanning

Masterplanning is a design process that is not regulated in any way. However, it does involve meeting statutory obligations. In the UK, a planning system is in place to ensure and maintain the integrity of the built environment in which the obligations are enacted by planning control. This is enforced with legislation under the remit of regulations and directives for each constituent country.

As an example, for England, the development of land is overseen by a local planning authority (LPA) who provide a planning policy through an associated local development framework. Planning permission is necessary in most cases concerning the development of land or buildings. It must be requested from the relevant LPA who grant permissions based on submitted development plan documents (DPD) and whether the requirements of the local planning policy and the relevant planning legislation are met. A basic interpretation of the planning system's influence is shown in Figure 5-2 which also includes the role of Masterplanning.

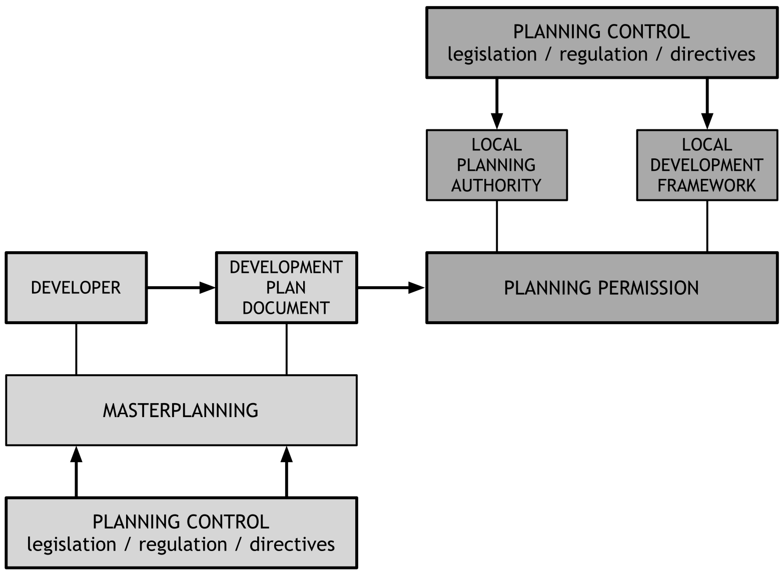

Figure 5-2: Masterplanning and the Planning System Structure.

With respect to Figure 5-2, a 'developer', as one who intends to take on a development or redevelopment project, obtains 'planning permission' by submitting 'development plan documents' (DPD). The figure interprets the planning system as two aspects. In short, the first half demonstrates the process of gaining planning permission, whilst the second half demonstrates the process of granting planning permission. Most notably, both are subject to planning control in the form of 'legislation, regulation, and directives'. Finally, it is demonstrated within the figure that masterplanning is a practice that feeds into the first half of the planning system. In reality, this means that the practitioners of masterplanning will support or even take on the role of the developer so that a successful DPD is submitted for planning permission approval.

Planning Control and Sustainable Development

For the planning sector, there is a great emphasis on sustainable development. In the recent National Planning Policy Framework (NPPF), a government mandate for the planning policy in England, it is commented that *"the purpose of the planning system is to contribute to the achievement of sustainable development"* (NPPF, 2012, p.2). Sustainable development is, as previously mentioned, enforced by legal obligation under the remit of planning law. Aside from being a design process and alongside adhering to statutory requirements of planning authority and policies, there is specific legislation that is relevant to masterplanning. The most prominent of which is summarised in the following points.

- The 2004 Planning and Compulsory Purchase Act requires a **Sustainability Appraisal (SA)** for the preparation of all DPDs which cover area action plans and any supplementary plan documents (SPD). The appraisal provides a sustainability assessment for the wider effects of the three dimensions key to delivering sustainable development. They are dimensions of economical, environmental and social basis. Such appraisals are an opportunity to identify the likely and significant effects of a development/redevelopment strategy or plan. Indicators relevant to the projects can also facilitate testing of performance in objectives relating to all of the three dimensions for sustainable development.
- Sustainability appraisals are carried out in conjunction with a **Strategic Environmental Assessment (SEA)**. This is required by the 2004 Environmental Assessment of Plans and Programmes Regulations as a requirement of the EU Strategic Environmental Assessment Directive 2001/42/EC. The regulation provides a guideline in defining the criteria to determine the significance of plans and programmes in relation to the framework of the project and other agendas.
- Specifically in terms of the environmental planning dimension, **Environmental Impact Assessments (EIA)** are necessary in large scale projects and therefore within the scope of masterplanning. This is required by the 1999 Town and Country Planning Regulations (England & Wales) as a requirement of the 2011/92/EU Environmental Impact Assessment Directive. With EIA, there is particular emphasis on making careful considerations and identifying significant impacts of a development plan that may arise as part of a planning proposal. This is in support of decision making with a prescribed criteria of assessment and recommended procedure.

5.2.2 The Extent of the Multiple Disciplines Involved and the Interdisciplinary Nature of Masterplanning

The integrated service provisions of masterplanning is often farmed out to consulting firms. In part, this is due to the large scale of the projects concerned and the significant scope of change. More prominently, it is due to the incapability of the developer to provide complete 'masterplans' as a form of development plan documentation (DPD) that can precisely detail all technical aspects that must be included. For example, the urban design of different land-use types, landscaping of open spaces, structural designs for built forms, strategies for infrastructure and the overall scheduling of construction.

Under the regard of sustainable development, masterplanning as an integrated service provision occurs with multiple disciplines involved and typically involves services of 'urban planning' and 'urban design' that see an integration of many different practitioners. The development of masterplans are heavily reliant upon the expertise of those involved. This extends from the policy and strategy developers, to the designers and technical specialists who aim to achieve plans that meet their client's requirements with regulatory approval.

Strictly considering the scope of masterplanning in preparation of the required DPDs, the different disciplines involved are all interconnected in some way. Although such connections are not explicitly demonstrated, Figure 5-3 shows the most significant disciplinary fields contributing to masterplanning and the general process actions involved.

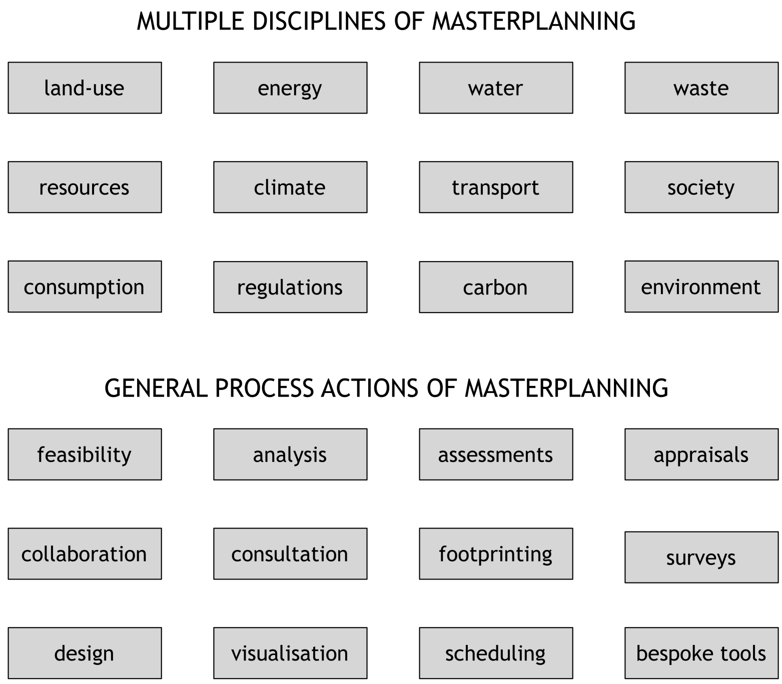

Figure 5-3: The Scope of Masterplanning: The Multiple Disciplinary Fields Involved and General Process Actions.

Using water as an example, several of the disciplines listed in figure 5-3 will affect the design and scheming of a water strategy within a masterplanning proposal. Strategies developed are dependent upon the demand based on the volume of water 'consumption'. This is determined by 'society' in relation to the consumption of the estimated population. It will also be based on the mix of 'land-use' in relation to the consumption of different land-use types. A few examples being open space, domestic residential use or non-domestic commercial use. Consideration for the different types of demand such as potable (drinkable) and non-potable water must also be made. In many cases, water will require treatment for its intended use, particularly 'waste' in the form of black (sewage) water. This has an impact on 'environment' but also requires 'energy' for treatment processes. Meeting water demand can also include supply strategies that may involve rainwater harvesting.

This is somewhat dependent on the local 'climate' of the area. Each decision will also have implications towards total 'carbon' emissions of the masterplan and the general 'resources' available. Finally, the appropriate 'regulations' must be met under statutory requirement. The completed water strategy must then be brought in line with all other relevant strategies such as land-use, carbon, climate, energy or waste.

This simple example only touches on the complexities of negotiating different masterplanning strategies but clearly demonstrates an inherent interdisciplinary nature. It also highlights how the differing disciplines or fields are in many cases likely to be mutually dependent. As such, this puts great emphasis on the practitioners to work well in an integrated manner.

Practitioners likely involved in masterplanning would include various analysts, architects and designers, engineers, planners, technical modellers and specialists, not only in general but also specifically from each field. For the many masterplanning practitioners, there exist various supporting tools and approaches that are to be discussed in the next section.

5.2.3 The Supporting Tools and Respective Approaches for Masterplanning and its Practitioners

Although considerations and compliance to facilitate sustainability development is a statutory requirement, the guiding legislation and regulations available are in reality, an underlying foundation towards masterplanning. As such, the regulatory frameworks and guidelines provide somewhat of an informally established code of practice or basis for modes of operation. Sustainability appraisals, previously mentioned as mandatory, are an example of this. In addition there exist key supporting approaches, tools and methodologies that are discussed within this section.

Sustainability Appraisals

Sustainability appraisals provide an expert assessment for the scope of achieving sustainable outcomes. In addition, appraisals may be considered as a product-service, especially when offered as part of integrated service provisions of masterplanning. In this case, sustainability appraisal would be provided as the product, and the consequent masterplanning would then provide a service.

For the built environment, appraisals ensure the principles of sustainable development are thoroughly considered and compliant with policy enactment at macro levels such as government or planning authorities. Hence, they support informed decision making by identifying and mitigating impacts (Spangenberg & Bonniot, 1998). Some of which may not always be initially evident. In support of integration, the appraisals provide a strong momentum for integrative working (İlal, 2007). This is, for the most part, due to the holistic nature inherently demanded from the many different fields involved within sustainable development. Hence, the same implications apply with associated practices such as sustainability appraisal. In essence, sustainability appraisal is a process in which the overall sustainability objectives are translated into practical actions (Spangenberg & Bonniot, 1998) as a result of what emerges through careful inquiry and investigation.

Furthermore, the use of sustainability appraisals has great merit as part of general urban designing process. This is considered to be also true of general appraisals in any design activity as part of the 'understanding' phase The advantages that exist extend from the outcomes of such appraisals that facilitate better decision making and more informed design practice. This reduces risk and the negative impacts of decisions that may occur when it is late in the process, for example at the construction stage, and difficult to make allowances or change decisions (Ugwu et al., 2006b).

The use of appraisals are most effective with a 'consolidated' approach or methodology (Ugwu et al., 2006b). Although not all aspects of sustainability appraisals can be objectively and quantitatively measured. Therefore, there needs to be some indication of performance outcome for an entirely comprehensive appraisal.

Performance Indicators

Performance indicators are commonly used to consider the elements of sustainable development in order to provide a comprehensive yet measurable outcome for sustainability appraisals and are considered to be planning tools (Hardi & Barg, 1997 cited by Farsari & Prastacos, 2002).

In general, the indicators of sustainable development facilitate the translation of sustainability targets into practical action by quantifying the strategy and objectives established by all stakeholders - government, authorities and developers alike. As such, they *"operationalize"* the principles of sustainable development (Farsari & Prastacos, 2002). In addition, indicators provide a performance-based process in which the indicators provide a measure of how well a masterplan will 'perform' against specific objectives. This is in contrast to a simple verification-based process in which designs are verified as able or not able to meet the objectives. Indicators related to performance provide an instant measure on one or several parameters of interest. In this way, they can also be used to measure progression towards preferred options and/or monitor the implementation of planning proposals and designs (Ugwu et al., 2006a).

Although there exist formalised efforts to specify indicators under the remit of sustainability appraisals, there is an underlying need for such indicators to be appropriate, relevant, quantifiable and understandable (Ugwu et al., 2006a). In addition, such indicators must use a transparent method of formulation and calculation. However, more importantly, they must consider linkages from the various sustainable development principles to maintain good *"operational qualities"* (Spangenberg & Bonniot, 1998, p.12).

Integrated Assessments

The demands of linking the principles of sustainable development with indicators can be addressed with the use of integrated assessments. Much like sustainability appraisals they are considered to be a product-service and therefore as much a process as they are an outcome.

Integrated assessments provide a mechanism to assess impact. Using performance indicators, in an integrated way, they are used to actively evaluate, compare and monitor the interconnections and interactions of a masterplan design proposals or solutions. At the same time, such integrated assessments have the ability to expose and reduce the complexities of sustainable development. Such assessments provide the functionality to efficiently differentiate impacts of different decisions but also guide the decision making process. This is between different scenarios through calculated trade-offs amongst the different indicators used (Jakeman & Letcher, 2003). In essence, integrated assessments are the ideal environment for the use of performance indicators in sustainability appraisals.

Integrated assessments are also often built to consider multiple disciplines and can therefore act as a collaborative and more importantly, integrative platform that requires features of interoperatability (İlal, 2007). They benefit and evolve from contributions of all forms of knowledge and continuous practice. However, current activities in the built environment do not always have the appropriate support or easy access to tools which facilitate integrated assessments. This includes those that are to be used as part of sustainability appraisals and for associated actions such as decision support (Ayaz & Levitas, 2008). In light of this, there exists much scope for advances in supporting tools (Jakeman & Letcher, 2003).

Computer-Aided and Modelling Support Tools

Projects based within the architecture, engineering and construction community (AEC) are traditionally based on precedence, experience or on a case-to-case basis (Clevenger & Haymaker, 2009). It is also largely based on a practitioner's tacit knowledge (Woo et al., 2004). For the many involved in AEC projects, it is said that the most prominent challenge lies in *"communication and coordination of information"*. This is between the many diverse disciplines involved that are often seen to be somewhat incoherent (Zamanian & Pittman, 1999). This issue is further compounded with the multiple perspectives of sustainable development and the requirements laid down, for example, by sustainability appraisals. In addressing the need to facilitate improvement there is a continuous move towards computer-based working.

Considered as *"the most multidisciplinary practice in all of the design professions"*, those involved in the built environment disciplines make use of computer-aided design (CAD) and more specifically, computer-supported collaborative working (CSCW). This is with an aim to improve general working practice, project management and information exchange between those involved (Garner & Mann, 2003, p.495). This is also despite the fact that CAD and CSCW approaches function around explicit knowledge and not tacit knowledge which is more associated with creativity and design professions. It is computational capability that works in favour of its use. There exist various computer-based support tools that facilitate CAD or CSCW for all specialist streams of the AEC community. Specifically for design and planning under the scope of sustainable development, there are tools that support technical modelling at various scales. For example, geographic information systems (GIS) software uses databases of spatially referenced data that allows interactive inquiry. This is to inform decision making with regards to land-use and topology.

Life cycle assessment (LCA) is supported by many software and modelling packages. It also supports decision making through databased information which is modelled into different options or scenarios. Finally, an example of a shared modelling environment can be seen in building information modelling (BIM). Considered as a form of 'intelligent CAD', BIM allows visualisations and modelling for the purpose of coordinated design and the integration of contributions from different disciplines for the design of a built facility. It often incorporates GIS and LCA elements that allows much design information to reside within one central model that is readily accessible to all, even within globally distributed teams.

In addition to supporting decision making and providing coordinated working environments, computer-aided and modelling support tools have allowed an increase in the capacity to communicate information contributing to the activity of multidisciplinary work. However, this does not necessarily improve the quality of such working (Garner & Mann, 2003). It therefore remains that CSCW has an opportunity to further advance computer-aided support and the associated fields that apply it. This continues to be true despite any current advances in CAD or CSCW.

5.3 Chapter Conclusions

In this chapter, the built environment has been demonstrated as a design-based field in part driven by legislation and statutory requirements, and most significantly affected by the issues of sustainability. It is therefore inherently interdisciplinary, and also complex. Such complexities have been identified as arising with respect to the influences of people, practice, and precedence. Masterplanning as a design-based practice and its associated supporting tools have been introduced and will further be explored in the remainder of this thesis.

The built environment is an example of a complex and interdisciplinary design-based practice. Therefore, it provides a useful forum for applying constraint-based thinking and associated techniques discussed within this thesis.

Chapter 6

Proposal of Constraint-based Thinking as a Methodology Towards Enhancing Complex and Interdisciplinary Design

"The framing of the problem is often far more essential than its solution" - Albert Einstein.

The research presented in the earlier chapters of this thesis is predominantly an exploration of the issues that may arise when designing is involved, and the issues of interdisciplinarity and complexity that can emerge as a result of the process and for the practitioners involved. This chapter begins by summarising the prior content and clearly identifying the significant conclusions and describes the potential opportunity to enhance designing indeed as a response to such interdisciplinarity and complexity by proposing constraint-based thinking as a methodology towards such design and accompanying issues.

6.1 Exploring Current Designing State-of-the-Art

The following sections describe the current state-of-the-art with particular respect to: perspectives of designing, constraint-based thinking towards design problem structuring and design space exploration, the impact of sustainability and finally, complex and interdisciplinary design within the built environment.

6.1.1 Perspectives of Engineering Design and Design Thinking

Chapter 2 explored the nature of designing and design-based thinking, to which a problem solving perspective was applied. Designing was identified most simply as problem solving or at the very least, being closely related. With respect to design-problem solving, understanding emerged as a significant element. Furthermore, creativity, designing, and cognitive process were all observed as being closely related to each other and rooted in knowledge which is especially considered to faciliate understanding.

6.1.2 Constraints, Constraint-based Approaches, and Constraint-based Thinking

Chapter 3 explored the idea of constraint-based thinking as being mindful of constraints and the consequent handling of, that might be used towards design-problem solving. Constraints were identified as particularly useful towards knowledge discovery relevant to problem structuring and representing design-problem spaces. Constraints as a means of understanding is considered not only for its potential contribution to design-problem solving but also for its ability to advantageously preclude and promote creativity and support designing.

6.1.3 From Sustainability and Sustainable Development to Sustainable Design

Chapter 4 explored the nature of sustainability and identified its integrated elements of people, planet, profit, and policy, and, the tools that are available for supporting sustainable development. Most prominently, the impact of sustainability was identified as being responsible for shifting principles in designing towards being increasingly interdisciplinary.

6.1.4 The Built Environment

Chapter 5 explored the built environment as an example of an interdisciplinary and complex design that is especially driven by sustainability, but also legal obligation. Furthermore, the interdisciplinary nature of the built environment and the factors of people, practice, and precedence, were identified as the inherent causes of complexity. The extent of this was explored in the example of masterplanning and supporting tools were also identified.

6.2 Responding to Complexity and Interdisciplinarity in Designing With Constraint-based Thinking

In response to the challenges of interdisciplinarity and complexity in designing, this thesis proposes constraint-based thinking as an approach towards enhancing complex and interdisciplinary design. In doing so, it attempts to answer the research question.

"Can constraint-based thinking be applied to enhance existing practice of designing and efforts of design thinking in order to support that which is both interdisciplinary and complex?"

A constraint-based methodology in general, is predominantly based upon acknowledging constraints and their consequent use thereafter. When chosen by the practitioners as an aid to designing process, constraints may be effective throughout and are integral to establishing the design problem as much as they are able to support design-problem solving. Their ability to enhance desiging is also supported in this thesis since they are especially adept at capturing and representing knowledge and facilitating understanding towards achieving optimised and/or acceptable preferred outcomes. Constraint-based approaches can also support designing very early on as constraints and design objectives are commonly and concurrently established together.

Applying constraint-based thinking means applying the mindset in which constraints are proactively acknowledged and formally identified so that they may be worked with as part of designing and design-problem solving. Therefore such thinking is mindful of constraints, how they are imposed, and the formal or generalised methods that are available and might be applied to enhance designing of a complex and interdisciplinary nature.

6.3 Methodology For Demonstrating Constraint-based Thinking Towards Enhancing Complex Interdisciplinary Designing

The thesis now continues with specifically applying constraint-based thinking as its proposed methodology. Shown in Figure 6-1, the methodology begins by obtaining a suitable environment in which design variables and their constraints can be defined, and is then populated. The interconnections between these are defined as constraints. From these, specific constraints are chosen to be explored. The exploration of these constraints then takes place.

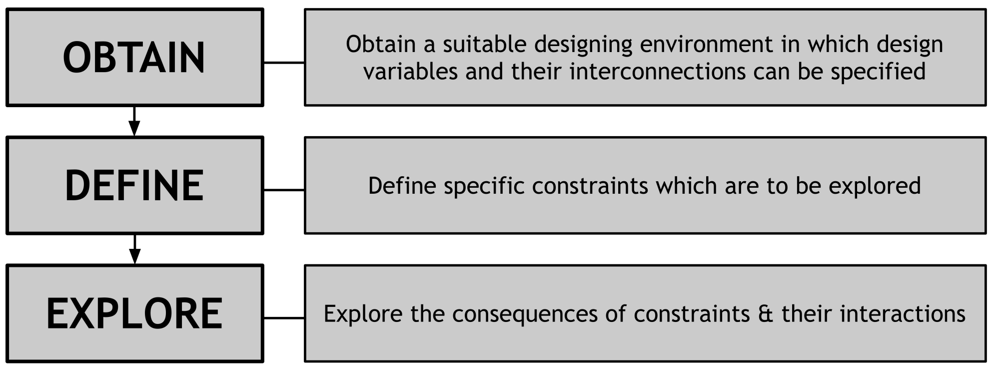

Figure 6-1: Methodology for Constraint-based Thinking.

This methodology is demonstrated using a series of case studies that collectively aim to demonstrate constraint-based thinking does indeed enhance existing designing and design thinking towards that which is both interdisciplinary and complex.

In the chapters hereafter, integrated resource management is explored as an approach towards masterplanning that is the specific setting for demonstrating the value of constraint-based thinking. Constraints and constraint-based thinking is then considered within the context of legislation and statutory requirements. This is followed by how general designing process can be translated with constraint-based thinking, and into constraints. Finally, a specifically created toolkit is presented as a methodology that has emerged from applying constraint-based thinking, and is based on constrained optimisation.

6.4 Chapter Conclusions

It has been proposed that constraint-based thinking is an appropriate methodology for interdisciplinary and complex design. This is a new idea but naturally comes from the current state-of-the-art.

Chapter 7

Investigating Integrated Resource Management

“The future belongs to the integrators” - Ernest Boyer.

Integrated resource management (IRM) is affected by sustainability, complexities that arise, and is fundamentally interdisciplinary. It therefore provides an ideal setting for demonstrating how complex interdisciplinary designing can be enhanced with constraint-based thinking. This chapter therefore investigates IRM and begins by exploring the fundamental principles of its nature and reports upon an empirical study based in industry. It discusses the observations that include how IRM is integrated into masterplanning and urban designing process, and also the implications regarding interdisciplinarity and complexity.

7.1 Understanding Integrated Resource Management

Design, particularly within masterplanning of the built environment is an increasingly complex and interdisciplinary practice to which both academia and industry continue to respond to with increasing vigour. One response can be seen in the application and development of integrated resource management (IRM). This section firstly considers the scope of IRM as designing and decision support. It then examines a previous case study before considering the scope of IRM's progressive emergence and further study herein.

7.1.1 A Perspective of Integrated Resouce Management

IRM has emerged as a designing and decision support tool and much like sustainability and sustainable development, it is rooted in the principles of managing natural resources with due care towards concerns and preservation of the environment. It provides an integrated working platform as a means of integrated assessment and/or appraisal that considers different scenarios and calculated trade-offs. When applied as a mechanism to assess impact, it is capable of exposing and reducing complexity. In general, the process focuses heavily around performance indicators that are most commonly translated from project objectives and are identified early on. They can be pursued as overall aims of a project but, as often is the case, may also be perceived to be limitations.

IRM and its associated principles in support of decision making can be applied as part of services regarding the built environment. Such services would include project management and masterplanning, be this in general, strategic or otherwise. In the following sections, a previous example of applying an IRM approach is explored and the progressive emergence of IRM is discussed.

A Retrospective Case Study of Integrated Resource Management Methodology

A case study carried out by the International Council for Local Environment Initiatives (ICLEI) illustrates and reviews the functional application of IRM methodology and its fundamental principles for the Municipality of Heidelberg, Germany (Kepran, 2002). The study itself recalls the actions and deployment of IRM principles towards a plan of improvements that was particularly considerate of sustainability issues and of sustainable development. Primarily, this was in response to challenges of 'people' or rather societal motivations. It included issues of unemployment, unaffordable housing and shifting demographics.

Having acknowledged that as a collective, so-called 'management-instruments' and methodologies that already existed would often work in isolation of each other, an overall more integrating approach was deemed appropriate. The application of IRM allowed for a consistent framework and provided an integrated working platform (Kepran, 2002) as an ideal core to the route taken towards achieving the specific aims and objectives of the municipality. The use of IRM was also driven by motivation to integrate varied strategies and policies of sustainable development.

The IRM framework specifically created for Heidelberg complemented the essence of other other techniques which also had a role in achieving successful results. For example, environmental budgeting was used to manage natural resources in a similar way to traditional financial budgeting process by using the mechanisms and routines to manage and budget for all natural resources *"as economically as artificial resource"*. In other words, resource in terms of money (Kepran, 2002). Additionally, the community used environmental 'indicators' that were measured in physical quantities. This being rather than direct impact in terms of environmental affect and alongside some level of economic consideration. In the case of Heidelberg, such performance indicators provided a bespoke yet objective measure of impacts and implications for various static or dynamic scenarios of alternative strategies. These indicators included carbon emissions, water consumption and residual waste generation, each set to five and ten year targets.

Creating a consistent and integrated framework using IRM and IRM principles provided Heidelberg with a structured approach to the challenges of improving and maintaining sustainable living for the municipality. It is an example in which the elements of sustainable development have been considered to the extent that success is as a result of the collaborative efforts to draft, develop, apply and maintain an IRM-based framework. The case of Heidelberg and its success provides the scope to further investigate the application of IRM methodology when handling many interlinking factors as part of an integrated process, for example, when contributing to sustainable development (Liang et al., 2008).

For IRM and the associated principles that are integral to carrying out such a process, a structured approach is deemed somewhat necessary. This is in order to effectively negotiate the integration of the many inclusive elements that may be involved. The use of performance indicators is not really considered to be a novelty but the use of an IRM approach in general, is still quite fresh. Its advantages lends itself well to many industries and has seen a gradual emergence within sustainable development, masterplanning and the built environment services and industries.

Progressive Emergence and Further Study of Integrated Resource Management

In summary of previous description, IRM has been described as a mechanism to assess impact and negotiate complexity that arises from interdisciplinary work. It provides an holistic yet detailed overview and acts as a design and decision support tool that provides an integrated approach, all in an attempt to ensure and follow the ethos of a sustainable design and development process.

In its own development, IRM has emerged as a support tool for mitigating and managing the issues of sustainability and sustainable development through scenario hypotheses and subsequent calculated tradeoffs. IRM has demonstrated a capability in supporting masterplanning (Page et al., 2008) and built environment services that are focused within the more formally entitled sector of urban design. This being the designing and development of towns and cities that forms the primary context to which the content of this thesis is relevant.

With whatever advantages IRM may have aside, it may be regarded as being somewhat of a complex approach. However, this is considered to be largely influenced by the many and varied specialist streams that are likely to be involved within the design and planning process. Complexity here, seems simply to be the 'nature of the beast', especially when dealing with issues such as sustainability and sustainable development, something so naturally complex itself. Fundamentally, the process of IRM is based upon a framework that evolves around performance indicators extracted from project aims and objectives but also alongside sustainability appraisals and environmental assessments (Page et al., 2008). The capabilities of IRM have indeed led to its progressive emergence and it is further studied in the remainder of this chapter which reports the findings of an industry-based investigation and empirical study.

7.2 An Empirical Study of Industry-based Integrated Resource Management

The basic principles of IRM are not particularly complex. However, to fully grasp the fundamental principles and its practice, to the point where IRM becomes actionable, requires more than a basic understanding. The following sections therefore aims to describe, in-depth, the relevant principles and practicalities of IRM through a case study within an industrial context and business environment. It also aims to identify and highlight the opportunities in developing enhanced design techniques for complex design at a highly integrated level.

7.2.1 Arup and its Approach to Integrated Resource Management

The setting for this industry-based case study is Arup, an innovative and leading global firm of practitioners who specialise in services for the built environment. These practitioners include consultants, designers, engineers, planners and technical specialists who all work under Arup's self-professed motivation to *"shape a better world"*.

Arup supports the used of IRM methodology and in response to this, an IRM modelling tool has been developed by Arup which is described by the firm as a *"quantitative urban metabolism tool"*. It serves to support the designing and development of neighbourhood, city and/or regional plans and policies, which are prioritised under the context of specific resource streams. These are invariably relevant to sustainability and sustainable development (Page et al. 2008 and Ayaz & Levitas 2008). Altogether, it makes for a highly interdisciplinary means of working.

The IRM modelling tool itself has many advantages and has been applied in masterplanning practice and ecocity projects, with success (Ayaz & Levitas, 2008). Predominantly, such modelling facilitates an 'interdisciplinary dialogue' amongst the many practitioners that contribute their expertise with regards to the various relevant resource streams involved. As such, it is indeed an example of highly integrated work that considers the issues of practicing the process of sustainable development within the context of the built environment. However, it is also an incredibly complex process than also handles much complexity itself. Hence, Arup, as an example of industry-based IRM, is appropriate case study material and worthy of investigation with respect to the objectives of the thesis.

An Overview of Resource Streams and Arup's Development of IRM Modelling

Arup's IRM modelling works on the simple premise of bringing together its practitioners with the motivation of effectively achieving project objectives. The model is spreadsheet-based and can include macros or models from other analysis, assessment and modelling tools. The practitioners include individuals from different disciplinary steams from various fields of expertise, all of whom contribute to respective resource streams within the IRM model. Some of these have already been previoiusly described in Chapter 5 (Section 5.2.2, Figure 5-3, p.58).

The contributions from each disciplinary/resource stream provide captured data and information specific to a stream's particular design strategy. When brought together, individual strategies from the different streams form an enormous volume of inputs that are then processed within the IRM model. This is through a series of calculations and equations that are fixed within the IRM model. The effect of integrating different disciplinary strategies and their consequent interactions are then summarised as a set of project outputs.

As an overview, Figure 7-1 (p.71) illustrates the flow of data within Arup's IRM model and provides an example of the most prominent streams that are involved and the respective data that is provided by and/or requested from each stream. It also shows examples of outputs that are created once calculations and evaluations have been made within the model.

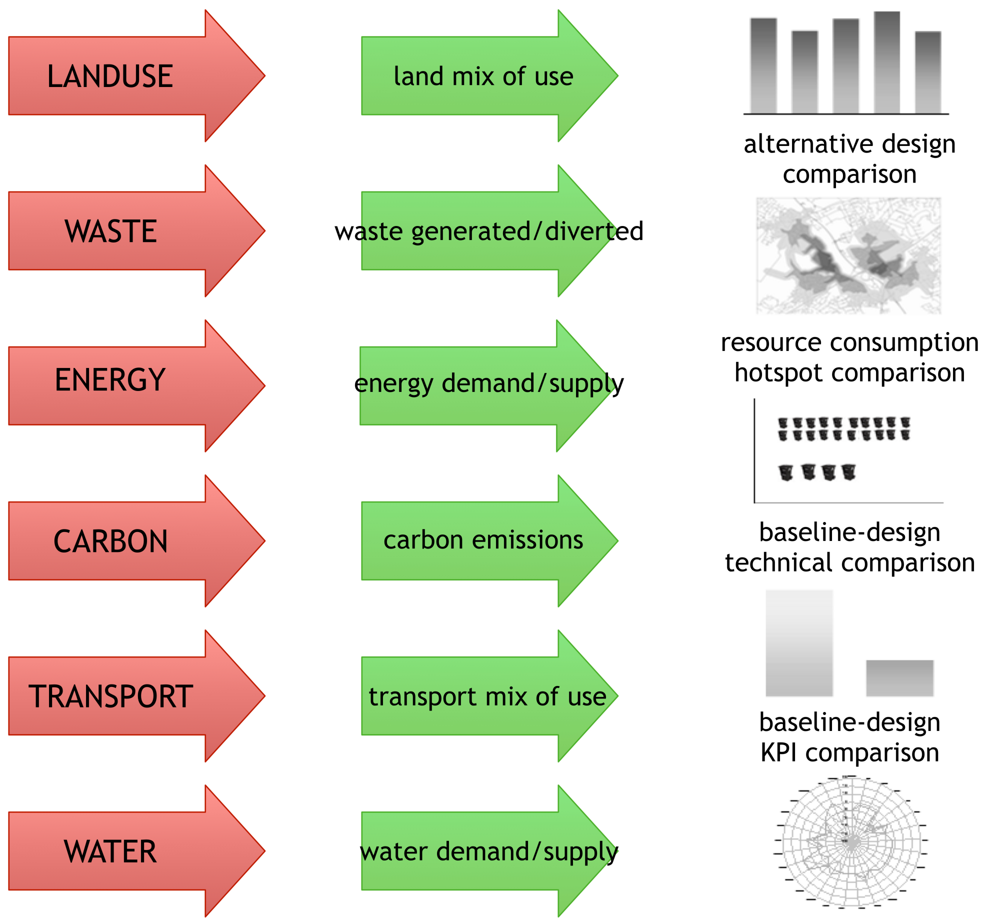

Figure 7-1: An Overview of Data Flows within Arup's IRM Model (Ayaz & Levitas, 2008).

Although all streams will make a contribution to the entire model, the practitioners of landuse are in essence, the overarching stream. Using information provided by a project's architects, the scheduling of land is determined with respect to how it is used in accordance to the intentions of the overall masterplan and the design strategy. Hence, the landuse stream takes somewhat of a priority and rather significantly provides a good starting point for all others.

Data from each stream is gathered and entered into the relevant 'input sheet' by IRM practitioners who are dedicated to overseeing the complete integrated approach. Each of these is simply a pro forma and each stream also has its own interim summary sheet. It is across all of these sheets that the input variables are evaluated through checks and equations set up within the whole model. For the final set of evaluated outputs, they are represented by, and take form as a series of metrics known as Key Performance Indicators (KPIs), the values of which are predetermined. They not only provide a measure of performance as targets to which the practitioners attempt to objectively achieve, they also represent the overall design, project and planning objectives. KPIs are an essential part of both IRM but also of masterplanning process.

Industry commonly labels design objectives as key performance indicators (KPIs) that often relate to targets and measures for success. Such indicators stem from the requirements of a design specification and can be both qualitative and quantitative. In IRM, the KPIs are related to land-use, buildings, people, transport, energy, water, and waste management, and would include, for example:

- Total carbon emissions per capita ($tC0_2$/resident/annum).
- Housing density (dwellings/hectare).
- Total electric energy consumption (kWh/annum).
- Proportion of travel by non-car modes (% of passenger-kilometres).
- Percentage of energy supplied by on-site renewables (% of total energy supply).
- Total potable water demand per capita (litres/person/day).
- Proportion of solid waste that is recycled, composted, or incinerated (% by tonne).

7.2.2 Arup's Approach to Applying Integrated Resource Management in Masterplanning

IRM when applied, is integrated into the full scope of Arup's masterplanning process which has previously been described in Chapter 5 (Section 5.2, p.54). This section describes how IRM and IRM modelling is specifically integrated into Arup's masterplanning process. It begins by discussing Arup's phases of masterplanning and how its sustainable designing process and particularly sustainability appraisals fit into this. Finally it considers the respective role of IRM and how it not only provides an integrated working platform, but is also integrated into masterplanning in general.

Integrating Integrated Resource Management and Masterplanning

Masterplanning, as an integrated service provision, is a process that involves many different significant phases that are not all design-based or actions solely of designing. Masterplanning is a provision that closely follows the Royal Insititute of British Achitects (RIBA) and their 'Plan of Work' model and also mandatory compliance respectful of UK planning law. The significant phases of masterplanning are shown in Figure 7-2.

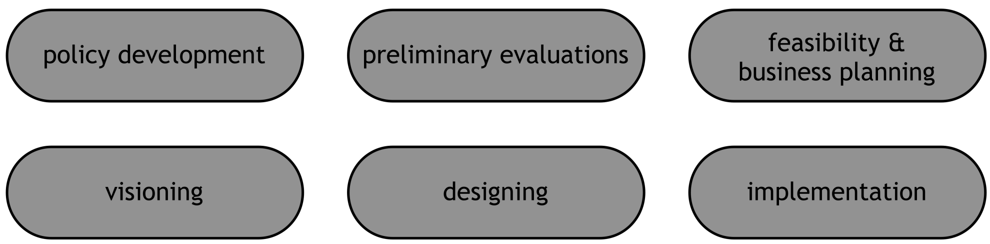

Figure 7-2: Significant Phases of Masterplanning

Although IRM is for the most part, relevant to all phases of masterplanning, it is predominantly applied as part of the ‘visioning’ and ‘designing’ phases, as seen in Figure 7-2, and is also applied earlier rather than later. In fact, when an IRM approach and IRM modelling is to be applied, it is done so at the point of finalising the masterplanning brief. At this point, it is where practitioners work with their client and/or stakeholders to form a unified and basic description of what needs to be achieved by the practitioners as a result of the processes involved. It is also the point at which overall aims such as sustainability objectives are declared from which measurables of performance, including key performance indicators (KPIs), may be directly extracted. Altogether, these actions contribute to the visioning phase of masterplanning.

The extent of masterplanning means that under UK planning policy, sustainability considerations must be made. In addition, sustainability appraisals and environmental assessments are mandatory. As a result, the visioning phase of masterplanning also includes creating a sustainability appraisal framework (SAF) which is inherent, not only to the masterplanning process and for achieving legal compliance, but also to IRM.

Definitively developing designing and project objectives through the masterplanning brief, the SAF and the KPIs is in itself a very integrating activity for the practitioners involved. Under the motivation of good practice, completing such activities concurrently has been intentionally set up by Arup to be this way. How these activities altogether contribute to and interact as part of ‘visioning’ in masterplanning is summarised and shown in Figure 7-3.

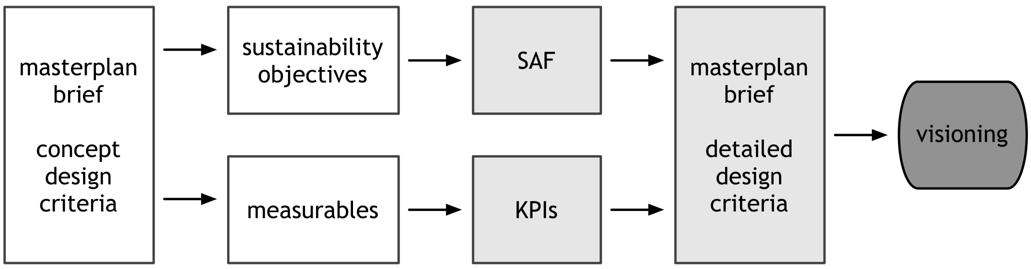

Figure 7-3: Developing Sustainability Appraisal Framework (SAF) and Declaring Key Performance Indicators (KPIs) as Part of the Visioning Phase in Masterplanning

On the left of the figure, the process begins with the masterplan brief and design criteria. From these, the sustainability objectives and measurables are extracted. From the sustainability objectives, the SAF is produced and this can be regarded as the global constraints of the design task. The measurables are represented by the KPIs and these can be considered also as constraints within a local capacity. These global and local constraints can then be regarded as elements of the detailed design criteria. Upon these, the visioning phase of masterplanning occurs.

Under the remit of masterplanning and urban design, the most basic requirements, whether sustainability related or otherwise, are established with regards to meeting mandatory compliances such as planning permission or regulations. These are relevant to the various planning authority requirements. Once the basic level of requirements are established, these objectives are then translated towards specifying different levels of aspirations that go beyond those of a simply statutory nature. That is to say, legal compliance is a minimum target of achievement, but more outstanding targets may indeed be set.

At Arup, such objectives are laid out and developed into a Sustainability Appraisal Framework (SAF) which occurs concurrently with establishing a project vision and/or the masterplan brief. Contributors to the SAF include various collaborators such as the client and/or relevant stakeholders. As previously mentioned, the basic requirements or equally the minimum design objectives are set by legislation or statutory requirements, and the regulations of the relevant (local, regional and/or national) planning authorities.

As the objectives are finalised, they are translated into a set of clearly defined, measurable and quantifiable KPIs. More simply, the SAF defines the objectives and therefore what is to be achieved. This is in comparison to the the defined KPIs which describe the measurables that allow the practitioners to evaluate if such achievements have been made, and to what extent. In addition, information provided by the practitioners of the various resource streams defines a baseline known as 'business-as-usual' (BAU). It is then used to set a benchmark from which general project targets or more ambitious targets may be developed and/or decided upon with respect to each objective. Differing sustainability aspirations are expressed from instances of BAU as either 'project' or 'stretch' targets.

Ultimately, finalising the range of objective target values for the KPIs, that is to say from mandatory to aspirational, means that the masterplan brief is finalised and forms a programme of detailed design criteria. It also completes the set up of the SAF which is fundamental to the crux of the IRM modelling approach as well as the masterplanning process in general. Not only are these actions key to visioning, they are also a significant contribution towards further activities in the following 'designing' phase and Arup's overall approach towards the outcomes of sustainable design practice itself.

Arup's Approach Towards Sustainable Urban Designing and Masterplanning

Following the visioning phase in Arup's masterplanning process, the formalised objectives that are emobodied and represented respectively by the sustainability appraisal framework (SAF) and the key performance indicators (KPIs) are used by the practitioners of different resources or rather specialist streams to develop their offerings of design options. Through appraisal of refinements and optimisations, the end of the designing phase produces a preferred (final) design which completes Arup's sustainable designing process. The actions that contribute to the designing phase in masterplanning are shown in Figure 7-4 (p.75).

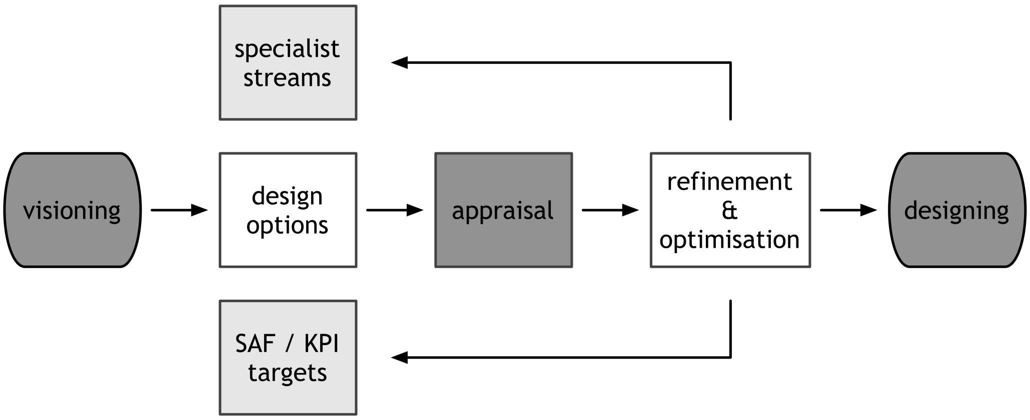

Figure 7-4: Sustainable Designing at Arup: From Visioning to Designing

The key actions as detailed in Figure 7-4 are notedly comparable with the abstract phases of designing models and are not too dissimilar from those previously reviewed in Chapter 2. The prominent action of 'visioning' is considered to be closely related the design-problem solving phase of establish. With respect to 'designing' in the context of masterplanning equally referred to as 'urban design', this is more comparable with respect to the design-problem solving phase of 'generate' and hence, generating a acceptable outcome. Also prominent in Figure 7-4, is the action of 'appraisal' which indeed significantly contributes to refinement and optimisation that yields the eventual outcome. As shown in the figure, but also observed in practice, the general action of appraisal is especially significant to masterplanning, and, is also considered to be in the same vein as the design-problem solving phase of 'understand'. In some ways, this further emphasises its importance to effective designing and also to the masterplanning process overall.

It should be noted that, with respect to the nature of masterplanning in terms of requirements to meet statutory approval, for example in order for developers (most commonly the client) to attain planning permission, the common interpretation of design process does differ somewhat. This is mainly with respect to the final outcomes which are often equally likely to be a series of design proposals and/or recommendations as opposed to one singular and completely optimised/preferred design outcome, or rather a solution that is to be immediately implemented or in the case of the built environment, constructed.

The next section continues by considering the importance of appraisal within masterplanning. It discusses the various design support types that are available, including IRM, and which are used in the designing phase, but also generally in masterplanning process.

Integrated Resource Management and Complementing Designing Support for Masterplanning

As part of sustainable designing shown in Figure 7-4 (p.75), in the previous section, there are many different types of designing support tools that are commonly applied.

DESIGN SUPPORT	TYPE OF SUPPORT
Sustainability Appraisal (SA)	appraisal tool/guideline
Strategic Environmental Assessment (SEA)	assessment tool/guideline
Environmental Impact Assessment (EIA)	assessment tool/guideline
Footprinting: Carbon, Environmental & Water	assessment tools
Geographical Information Systems (GIS)	data capture/assessment tool
Life Cycle Assessment (LCA)	appraisal/optimisation tool
Sustainability Project Appraisal Routine (SPeAR)	appraisal/optimisation tool
Integrated Resource Management (IRM)	appraisal/optimisation tool

Table 7.1: Designing Support Tools for Masterplanning & Urban Design

The tools that are most specific for masterplanning practice at Arup have been categorised and are listed in Table 7.1. Of the tools described in the table, they are predominantly either assessment-based or appraisal-based. In this thesis, the designing support is deemed to be assessment-based when offering general evaluations of performance. In direct contrast, they are deemed to be appraisal-based when offering evaluations that are with respect to value generated and/or quality of performance.

Appraisal-based tools, therefore including IRM, are without doubt common place within the remit of sustainability and sustainable development, hence their application as part of Arup's own sustainable approach to masterplanning and designing. This is especially true when considering some appraisals, for example, sustainability appraisal (SA), strategic environmental assessment (SEA) or environmental impact assessment (EIA), are explicitly mandatory. Furthermore, they are examples of designing support that facilitates decision making towards the development of preferred design outcomes and the process of reporting design recommendations. Whilst each appraisal tool has its own redeeming features, practitioners may benefit from using different ones alongside each other. In fact, designing support tools whether appraisal-based or otherwise, are rarely used in any uniquely individual capacity. In practice, designing support such as those described in Table 7.1 (p.76) invariably contribute to IRM appraisals as part of applying an IRM approach.

Specific to the case study of Arup, it has been observed that IRM as a complete methodology and sustainability appraisal are types of designing support that not only support each other, but are useful appraisal tools in general design. In the case of Arup, when IRM is indeed applied, it is an approach intrinsically linked to sustainability appraisal. These are both integral to masterplanning and urban design and the next section discusses how these are fundamentally integrated with masterplanning and urban design.

The Natually Integrating Processes of Masterplanning and Urban Design, Integrated Resource Management, and Sustainability Appraisal

Masterplanning and urban design, integrated resource management (IRM), and sustainability appraisal, are singularly processes within their own merit. With respect to Arup's case, all three are naturally integrated by the actions of definitively declaring the masterplan brief, the SAF and the (project and stretch) target values of the KPIs, at the same time. They are then intended to concurrently progress in tandem. Figure 7-5 shows the three processes masterplanning and urban design, IRM, and sustainability appraisal. It also attempts to describe the basic chronological nature and sequence of key actions and/or phases of each singularly individual process. The most prominent of the key actions and/or phases that make up the integrated processes shown in the figure, are highlighted. They represent those that are considered most integrating by nature and those of most interest within the context of this thesis. The figure also shows how these relate to visioning or designing with respect to activities that are key to Arup's masterplanning.

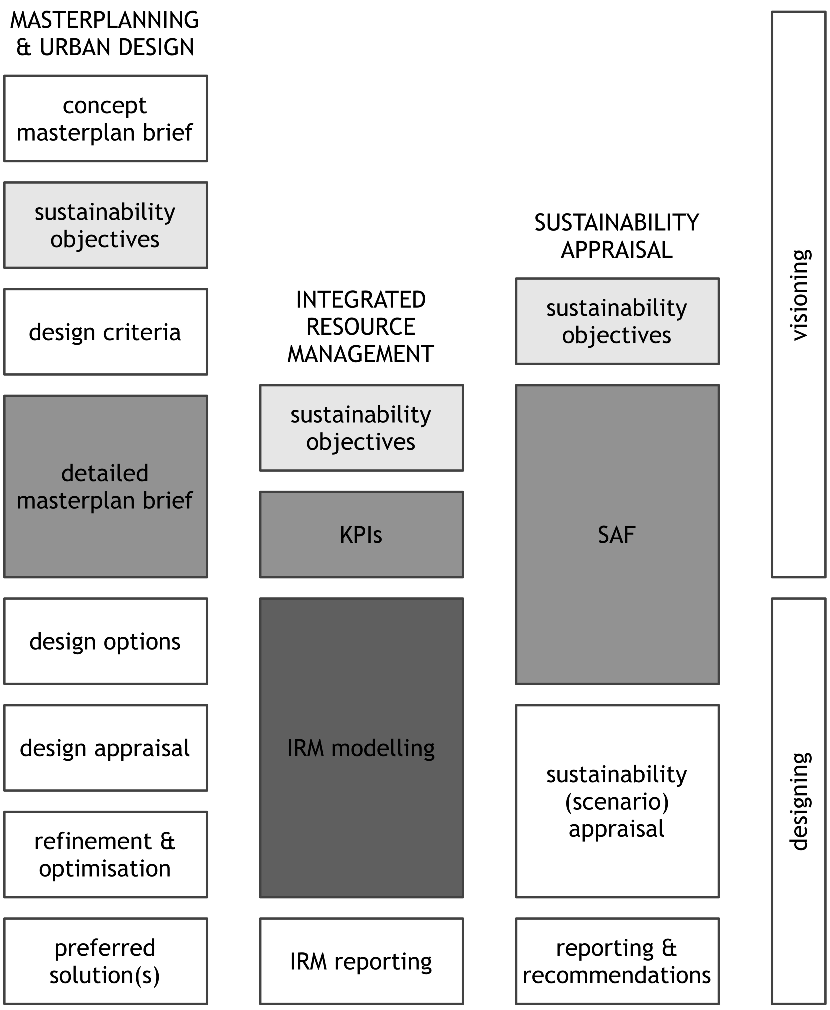

Figure 7-5: Integrated Processes: Masterplanning & Urban Design, Integrated Resource Management, and Sustainability Appraisal.

Most notedly, when considering Figure 7-5 (p.77), 'sustainability objectives' (shaded in light grey) are of the utmost importance to the three processes when integrated togther. Such importance is largely owed to the fact that these objectives represent the requirements that must be met by design and hence form a series of common goals to be achieved by all practitioners and stakeholders involved. Furthermore, assessments and/or evaluations carried out as part of 'appraisal' or for measures and notes of success in the design phase such as 'preferred solution(s)' or 'reporting and recommendations', are always measured against the very same sustainability objectives. They are therefore fundamental not only to the integrated processes as in Figure 7-5, but also to the various assessment-based and appraisal-based tools that may be used to provide design support.

Sustainability objectives are of paramount importance and consistently applied or referred to whilst the action of declaring the 'SAF', 'KPIs' and the 'detailed masterplan brief' using the objectives no less, is especially significant to the integration of the three processes to which the actions belong to as part of. Such actions in essence create an integrated vision and are prominent in completing the visioning phase of masterplanning, which has previously been shown in Figure 7-3 (p.73). As a series of intended actions, they are considered to be integrating because each contributes in turn to another and to some degree, each process cannot be completed entirely on its own without the contribution of another. These integrating actions (shaded in medium grey) in Figure 7-5 (p.77) are purposely shown alongside each other because they occur concurrently in practice. They are also considered to facilitate integration because all practitioners and stakeholders of all disciplinary and resource streams must contribute and are involved as far as being practically possible in the early stages of such design and project work.

Moving forward with the integrated vision, the design work begins. In particular, the SAF and KPIs are used directly as motivation and clear objectively defined goals as being that which practitioners aim to strive towards. As part of 'designing' in general, IRM modelling may be applied as a supporting tool. Since the KPIs that form the crux of the IRM approach are established as part of the integrated vision, the processes of design and sustainability appraisal are in many ways already linked. The integration of all processes becomes more so when IRM modelling is indeed applied. As shown in Figure 7-5 (p.77), IRM modelling runs concurrently between the general actions of masterplanning and urban design and sustainability appraisal. It integrates the practitioners involved by consistently demanding them to converse and make exchanges between each other upon the matters of their own respective actions such as design strategies, and the consequences thereof. Most simply, IRM modelling facilitates an integrated level of working primarily through establishing a common forum and shared data/information space. Here, the effects and influences be they conflicting, progressive or otherwise, must be appraised together and hence in an integrated way. This is by predominantly using the predetermined integrated vision and KPIs. Furthermore, IRM modelling is supportive of the 'designing' phase, as per the actions included in Figure 7-5. In the initial stages, it may be used to scope out 'design options' before they become more developed whilst later on within the 'refinement and optimisation' stage, IRM modelling can provide a means of decision support. It also naturally complements 'design appraisal' and 'sustainability scenario appraisal' since it is an appraisal-based tool itself.

Having observed IRM and its role within the general masterplanning process at Arup, it seems apparent that IRM modelling is not just a tool to be applied in an 'as-and-when-required' manner. Rather, it is a methodology that practitioners and/or clients consciously choose to subscribe to before any undertaking of design to be most effective, and is chosen on the premise of its capabilities.

7.2.3 Implications of Integrated Resource Management in Masterplanning at Arup

The capabilities of IRM are largely founded upon the augmented and integrated environment of aggregated data and/or information that provides various practitioners with the ability to observe and manage the holistic implications of design decisions and change. This is within the associated activities and iterative nature of designing. A particular advantage of IRM is that it allows complexities between the relevant specialist, technical and/or resource streams to be exposed. This is with respect to the interconnections that inherently exist, but also those that shall inevitably emerge as a result of interaction and data/information flow between IRM streams in general.

Figure 7-6, (p.80) demonstrates the scope of interconnections and data flow between the different IRM resource streams. Here, the green boxes represent the elements of resource streams found in IRM. These are the main into which a typical masterplan design is subdivided. Within each, there are constraints between the local design parameters. The orange boxes represent the interconnections between these streams, and hence the interdisciplinary constraints between design parameters from the various different resource streams.

The figure provides a small insight into the naturally integrated nature of masterplanning that is considerate of a sustainable designing approach. The influence of these interconnections and complexities that arise are discussed in the following sections.

The Influence of Interconnection in Integrated Resource Management

Figure 7-6, (p.80) shows the dominant streams such as 'landuse schedule, energy, waste management, water, passenger transport, and population' amongst others, and provides simple examples of how these may interact with each other. It shows an incredibly simplified view of how streams interconnect and how they may interact. Considering this only represents a very basic level of interaction between the IRM streams, it is not difficult to envisage encountering complexities when dealing with the full range of interactions that would occur during stages of detailed design, for example. Suffice to say, support in handling such complexities would be most welcomed by the practitioners involved.

Overall, it is the capability to negotiate complexity with an (imperatively) integrated effort from the practitioners of the IRM streams, that provides many advantages. It facilitates a more efficient exploration of alternative design options and at various levels of detail whilst ensuring a consistent expectation of outcome and alignment of design effort. It provides the potential to invariably increase the efficiency and effectiveness of those altogether involved.

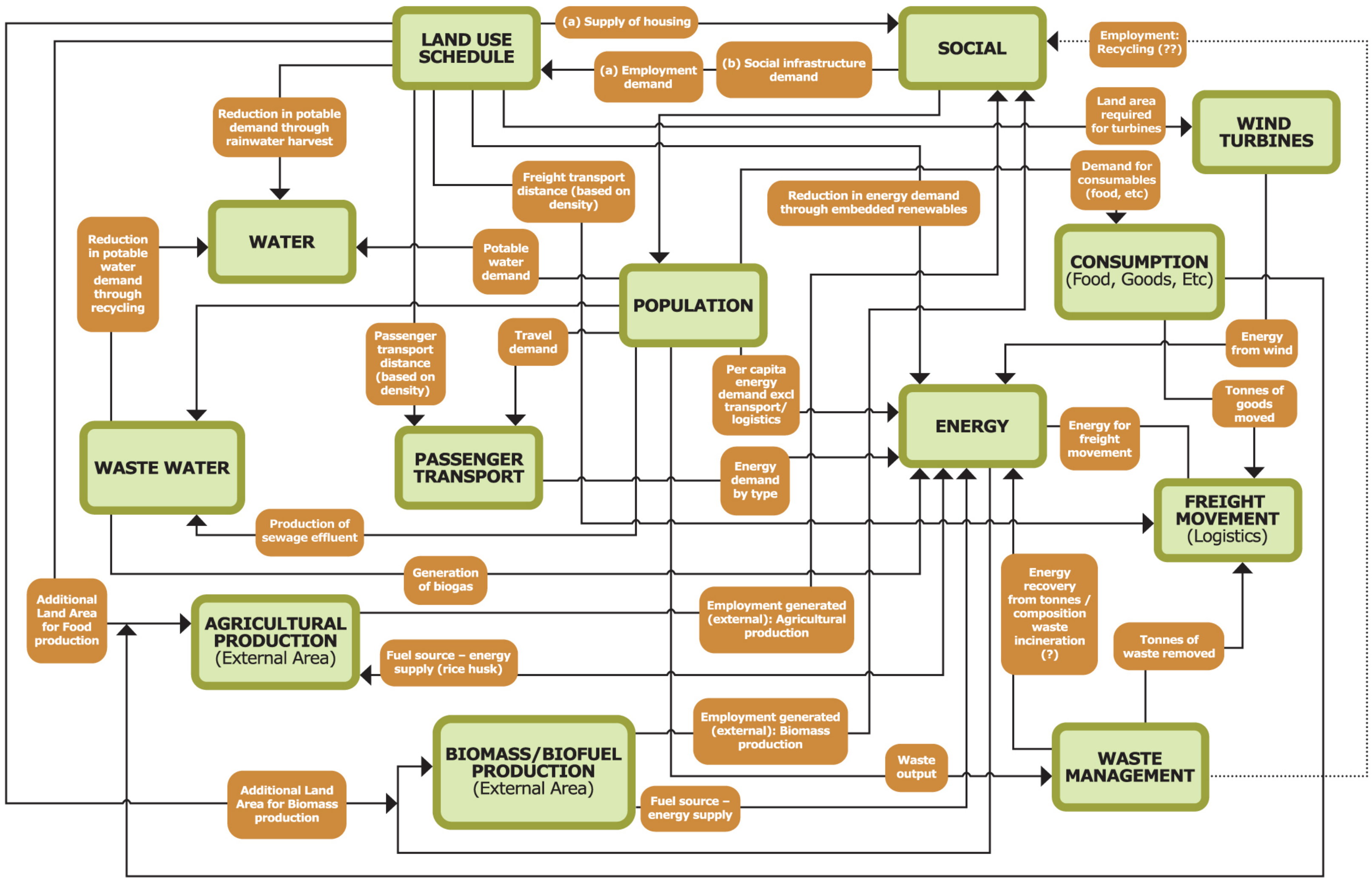

Figure 7-6: The Scope of Interconnections and Data Flow Between the Resource Streams of Integrated Resource Management.

Furthermore, as the designing process moves into its more advanced stages and therefore from considering potential design options to iterations of refinement and optimisation, the design support provided by the IRM approach and modelling tool becomes increasingly progressive. To begin with, IRM modelling requires input from the overarching stream of landuse. However, as other streams make their contributions, increased input and eventually increased design knowledge allows the implications of interactions to emerge between each of the streams. This is useful on occasions where the strategies of individual streams may result in conflict and in revealing data gaps or missing information that may be pertinent to design development. It is also useful in building practitioner awareness of opportunities and design strategies that may be more appropriate and successful than others. Hence, providing the scope to support an efficient and more timely route to preferred design solutions and/or final recommendations.

During designing, the aggregation of design data and bringing together design knowledge within an IRM model, provides easy accessibility and assessment of potential masterplanning design options and the associated information that is tied-up within these. Such information, once formalised, can also be used partly as contributions towards other supporting design tools that may be applied concurrently or at other points along the designing process. As refinements and optimisations are made, appraisal against the predetermined KPIs that represent sustainability and/or project design objectives can provide decision support to the practitioners, also decreasing the length and time of iterations. Later on in designing process, as well as designing support becoming increasingly progressive, IRM modelling increases the effective level of integration between the practitioners by simply having facilitated previous integration. In essence, IRM modelling ensures that everyone has been on the same page and has been going the right way, and therefore overcoming elements of the more traditionally fragmented and less integrated approach (Page et al., 2008).

The Arising Complexities in Integrated Resource Management

Despite its capabilities and associated advantages, there are some implications with respect to an IRM approach and the IRM modelling tool that should be additionally considered. As a complete methodology which aspires to integrate those involved in the process, it requires a particular level of dedicated practitioner participation. At Arup, IRM is predominantly driven by specifically assigned 'IRM practitioners' who are unable to provide specialist/technical input data for each and every individual stream. Therefore, IRM methodology requires absolute participation and willingness to collaborate from those of each stream. This becomes most significant when ensuring that IRM is effectively applied. In the same way that masterplanning is heavily reliant upon the expertise of its practitioners, IRM is heavily reliant on the same practitioners participating together and from the very onset of designing. Another absolute requirement of IRM methodology is not so much with the participation of the practitioners but more so with the need for IRM to maintain a certain level of flexibility. Masterplanning projects and urban design are most commonly unique and as design problems, they are unlikely to ever be identical. Therefore, each preferred design solution and the recommendations made at the end of the designing phase are in essence bespoke and specifically tailored for the respective design brief.

The complex nature of sustainable masterplanning and urban design is reflected within the generic nature of IRM modelling which owing to the level of integration in which it aspires to achieve, is also complex. In part this is caused by the sheer volume of highly interrelated data and design variables, in the order of hundreds, that are held within the model and are in some way dependent upon each other. Aggregating such a volume of data variables is obviously not without its difficulties although overall using the methodology is advantageous in outcome. Complexity within the IRM modelling tool and IRM methodology in general is a feature in which there is no other choice but to deal with and manage, simply as a matter of course - it is the nature of the beast. In addition it is recognised that there are other challenges that may be relevant and need to be considered when applying IRM methodology. This can be distinguished by their relevance to 'people, practice and precedence' described in Chapter 5, and is summarised in the following points.

- **Challenges and Complexity Arising in People -** 'Developing' a relationship for the disciplinary streams involved in order to facilitate more integrative working. To mutually maintain a consistent understanding towards achieving the objectives as per the masterplan brief and SAF and for all streams to hold confidence in each other.
- **Challenges and Complexity Arising in Practice -** 'Negotiating' different modelling practices used uniquely by each of the individual disciplinary streams. This includes the use of differing terminology and outputs that represent the same entities which need to be aggregated within one single modelling environment.
- **Challenges and Complexity Arising in Precedence -** 'Overcoming' the precedence of a somewhat disjointed setting between the disciplinary streams and the more conventional approach of 'throw-over-the-wall' data sharing for design. To facilitate an open environment and integrative working in AEC mulitdisciplinary practice.

7.3 Chapter Conclusions

This chapter has presented an investigation of integrated resource management (IRM) and reported an industry-based case study of an approach towards IRM and the consequent methodology. It has offered insight into an approach that integrates designing and sustainability appraisal, which all together, supports the masterplanning process. The scope of IRM examined within this chapter that presents the issues of interdisciplinarity and also complexity, is the setting for the remaining chapters.

In this way, IRM has been demonstrated as a means for handling complex and interdisciplinary design. However, it still has its own complexities which has presented an opportunity to which constraint-based thinking can be applied.

Chapter 8

Constraint-based Thinking: Legislation and Statutory Requirements

"Rules and responsibilities: these are the ties that bind us" - *Neil Gaiman*

Legislation and statutory requirements set objectives that require mandatory compliance, which is in fact, regardlessly achieved in all cases. They are equally considered to be a form of constraints that arise, and that must not be violated. Such constraints can be perceived to be a hindrance, especially towards achieving nominally creative or innovative outcomes. However, this chapter demonstrates that such constraints in the form of legislation and statutory requirements, nonetheless provide positive stimulus in designing. It begins by considering its impact, then presenting a case study of product-related legislation, and is followed by a study of process-related legislation.

8.1 Impact of Legislation and Statutory Requirements

Legislation and statutory requirements are forms of constraints to which all designers and practitioners are responsible with respect to achieving compliance. As such, they are observed in the form of collective laws or as standards that are set by regulating authorities. However, they are like all constraints - not all bad. Whilst the impact of these do weigh heavily as these constraints must under no circumstances be left unsatisfied, they are invariably and regardlessly achieved, in all cases. The general response to constraints in this form are considered to be a positive stimulus towards general designing and this thesis considers such constraints to have a positive impact.

The next sections discuss a case study in the context of product-related legislation and another in process-related legislation. Both are industry-based and with respect to constraint-based thinking, demonstrate innovative responses.

8.2 A Case Study in Product-related Legislation and Statutory Requirements

This section discusses the results of an industry-based case study first presented by O'Hare et al. (2007) and the investigation of innovation capability and environmental considerations of design and manufacturing. This is with respect to businesses that are affected by product-related environmental legislation.

8.2.1 Exploring Product-related Environmental Legislation

The study predominantly aimed to gain an understanding of real business practice and the design activities affected by the directives: Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and/or Energy Using Products (EuP). However, it was also aimed at obtaining further insight into the validity that eco-design has in fact been driven by such product-related environmental legislation (Pascual & Boks, 2004 cited by O'Hare et al., 2007).

Investigated Capabilities of Innovation

Innovation capabilities were primarily investigated as part of the study within the context of new product development (NPD). As part of mapping the specific NPD processes of the different businesses, concerns and scope for significant improvement emerged regarding formalisation of objectives through creating the product requirement specification. In addition, as suggested by Olundh (2006) (and cited by O'Hare et al., 2007), the study identified the point of developing the requirements specification as the predominent opportunity for methods to also integrate environmental considerations. Perhaps owing to limitations of the study, findings regarding innovation capability in NPD was somewhat limited. However, innovation and the potential for it seemed to emerge more so when investigating design activities with respect to environmental constraints and performance. This is discussed in the next section.

The Impact of Considering Environmental Constraints

The investigation into environmental considerations and response to legislative constraints revealed that for the most part, to achieve compliance, environmental impact was reduced though the optimisation of the production process. This was exposed as a result of life cycle thinking and demonstrated that even constraints such as emergent legislation still allows for opportunities to innovate although the potential to do so may not always be where initially or most likely thought. The study reports that reducing environmental impact did not lie within the actual product design perhaps burdened by the precedence of already rigid/specific requirements and therefore overly constrained. Instead, opportunity to affect change was sought elsewhere by considering production implications of the designed product when making life cycle considerations. As a result, this incited increased dialogue between businesses and their supply chain. In some respects this revealed an integrated approach reminiscent of the integrated product development model that considers market, product and production as proposed by Andreasen & Hein (1987).

Under a perspective of systems thinking, this suggests that when one system is highly constrained such as product design, another being production, is looked upon as an opportunity to innovate an overall change. Therefore integrated systems, regardless of their complex nature are still forums for creative efforts. The route of production optimisation as a potential to reduce environmental impact was suspected to have been encouraged due to interest towards cleaner production and direct cost savings through reduced energy and/or the minimisation of waste. Rather interestingly, the aspects of energy/resource efficiency were not always direct demands of the businesses' customers. Response to the product-related legislation was not particularly aspiring and found in some cases to be conducted at the minimum level of compliance thus legislation can be somewhat of a driver for environmental consideration and/or eco-design.

Separate to achieving legislative compliance yet consequently contributing to it, general efforts to save on costs by some businesses led to benefits that lessened environmental impact but, were not especially recognised as so by the businesses themselves. As proffered by Fiksel (2012), this supports the idea that sole environmental efforts will not always lead to financial benefit but its consideration within the scope of impact and trade-offs will often reveal opportunities and enhance satisfaction with respect to the customer, the business and profitability or competitive standing. Diversifying the mindset of practitioners to see positive benefits across a wide breadth and not just within a singular context such as environmental impact has been of noted importance and value for success of integrating eco-design activities into product development (Johansson, 2002 cited by O'Hare et al., 2007). Most prominently, the approach of life cycle thinking shows advocation of an integrated approach in which considering many different elements of different systems can all together produce opportunities for innovation in the eventual and overall outcome. This is despite the imposed constraints in the form of environmental product-related legislation as discussed. Overall, interest within the case study pitched towards eco-design, often seen as the onus of sustainable design and development (Liang et al., 2008), considers activities that are fundamentally inclusive of the basic principles of sustainable development: people, planet, profit and policy (Section 4.1, p.42). Here, they are equivalent to customer requirements and product users, environmental impact, needs and wants of the business and, standards or rather legislation and statutory requirements respectively. In the thesis and in the literature, systematic consideration of these such elements are broadly synonymous under the interchangeable labels such as eco-design and sustainable design (Fiksel, 2012).

8.3 A Case Study in Process-related Legislation and Statutory Requirements

This section discusses the results of an industry-based case study and empirical investigations conducted at Arup as part of the investigations in the previous chapter. This study is with respect to masterplanning and the use of integrated resource management that is affected by process-related sustainability legislation.

8.3.1 Exploring Process-related Sustainability Legislation

The study predominantly aimed to gain an understanding of industrial practice and specifically the masterplanning activities affected by: the 2008 Climate Change Act 2008, the 2004 Planning and Compulsory Purchase Act, the Strategic Environmental Assessment (SEA) Directive and the Environmental Impact Assessment (EIA) Directive. In contrast to eco-design being driven by environmental legislation, this section also aimed to investigate similar validity in the assumption that sustainable design is driven by process-related sustainability legislation, respectively. In addition, it aimed for further insight into how a business within the built environment might innovatively respond.

The Impact of Considering Sustainability Constraints

For masterplanning, compliance of process-related legislation is necessary in order to be granted planning permission. It is dependent upon the actions of the practitioners at Arup who are commissioned and therefore responsible for creating the mandatory Development Plan Documents (DPD) that are submitted on behalf of the developers, or rather the customers. This process has been previously described in Chapter 5.

Overall, legislation that primarily acts upon urban design and masterplanning is the Climate Change Act 2008 (HMSO, 2008) which has created a legal obligation for accountable contributions towards achieving targets of reduction in greenhouse gas emissions. This includes a carbon reduction of 80% for the year 2050 against 1990 baseline figures. Pertaining to this Act, the general obligation for low carbon emissions is commonly integrated into the underlying aims of all design and planning activity within the built environment which, is itself considered inextricably linked to the issues of sustainability and sustainable development (Section 5.1.3, p.52). The point at which low carbon objectives (and other greenhouse gases) are formalised into a requirements specification was noted in the previous study (Section 8.2, p.84) as being significantly important but was also marked for improvement. This is not considered to be the case for Arup who conscientiously develop their objectives and take the opportunity to fully integrate environmental and wider sustainability concerns. This is with full practitioner and stakeholder participation and also supports the previous note made in the literature (Olundh, 2006). Therefore, as part of the visioning phase (Figure 7-3, p.73) and approach to sustainable design of urban design and masterplans (Figure 7-4, p.75), this demonstrates a strong effort towards the formalisation of naming specific 'sustainability objectives' and also shows how the legislation has driven carbon reduction as a sustainability concern to be consistently yet inherently made. Thus it is considered to be a driver for sustainable design.

Between the requirements of the Climate Change Act and further afield, the impact of masterplanning upon the built environment means that it is subject to many other legislative obligations. In general, these are dependent upon the type of development and/or project. For an urban design or masterplan in the context of the study at Arup, and in order for compliance to be met, process-related sustainability legislation will in all cases, likely require sustainability appraisals and various strategic, environmental and impact assessments to also be carried out.

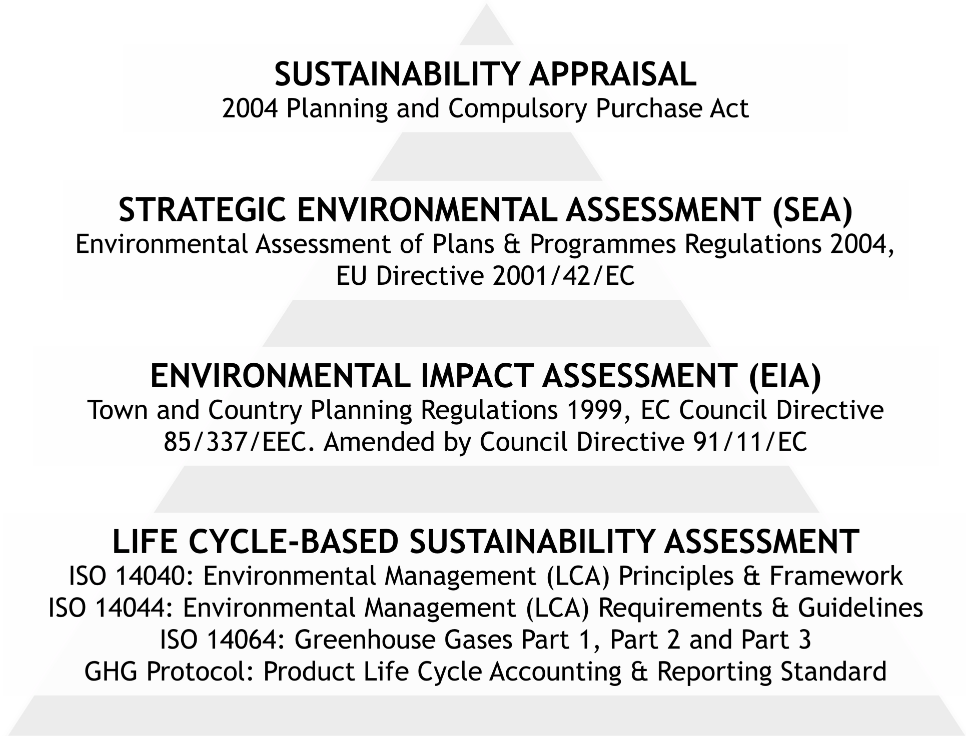

Figure 8-1: Sustainable Development: Hierarchy of Legislation/Guidelines.

As part of masterplanning and urban design, legislation to carry out specific appraisals and assessments are not all bad. Such legislation also offers practitioners with the tools and guidelines appropriate for achieving compliance. Such legislation, although imposes upon design process by dictating certain necessary actions, it also provides the scope for supporting consistently systematic approaches that contribute to good design practice as effort towards sustainable development in general. Along with additional standards set by the International Organization for Standardization (ISO), the relevant legislation introduced at the beginning of the section may be interpreted as part of a hierarchy that is demonstrated in Figure 8-1.

Figure 8-1 shows activities that are mandatory but have emerged as inherent within the process of sustainable development in urban design and masterplanning. Beneath each of these are the standards or legislation that drives the action of doing each activity. This is whilst also providing appropriate tools and complementary guiding legislation for how these activities should be done.

Figure 8-1 can also be regarded as a hierachy of hard constraints. As one comes down the hierachy the constraints become more specific and relate to specific areas of the design. As these are all hard constraints, they must be satisfied and this is an appropriate stimulus to the way the designer needs to think. The designer will typically work from the foot of the figure upwards, and in this way, from the specific to the more general constraints.

Life cycle-based sustainability assessments in general direct a process based around goal definition, inventory analysis, impact assessment and improvement. Developing an LCA framework to ascertain the environmental interactions and impacts can often be somewhat subjective - hence there is an underlying need for standards that exact some form of consistency. LCA differs slightly to Environmental Impact Assessment (EIA) seen in the level above within the hierarchy, as it aims to identify the potential significance of environmental impact for specific aspects of a proposed scheme or development and its consequent DPD. To name but a few, examples include planning and policy content, human population, air quality, geology and ground contamination, water resources, ecology/nature conservation, landscape, traffic/transportation and the interaction of such cumulative impacts. Therefore, the directive to carry out EIA and the guiding legislation regulates specific criteria considered for assessment and again providing consistency within sustainable design.

In the next level up within the hierarchy, the legislation moves on from dictating the assessment of specific impact to that of strategic plans and programmes in a wider context. Strategic Environmental Assessment (SEA) determines impact of a scheme/development and its strategy in relation to say community-based legislation that might already be in implementation such as waste management or water protection plans. In essence, the directive facilitates the wider alignment of sustainability criteria in consideration of other related legislation therefore aligning the design and the implemented strategies. The requirement for SEA is accompanied by mandatory obligation of sustainability appraisal which is at the top of the legislation hierarchy of figure 8-1. In practice, SEA can be integrated into sustainability Appraisal using the guidelines provided by government for 'Sustainability Appraisal of Regional Spatial Strategies and Local Development Frameworks'.

Sustainability appraisal at the top of the hierarchy is necessary in order to demonstrate a contribution towards lowering impact with respect to the Climate Change Act 2008. Each of the assessments in the levels below are individual processes that contribute towards it and demonstrates how process-related sustainability legislation supports sustainable design at each level by setting underlying requirements on the actions necessary. Many of these themselves have since emerged as inherent to sustainable design and are indeed designing support tools significant to urban design and masterplanning at Arup.

The Response to Process-related Sustainability Legislation

The process-related sustainability legislation when considered to be a form of constraint, imposes specific design actions but is not seen as a hindrance to sustainable development. The varying levels of legislation and hence the varying level of constraints actually make the process more manageable and if anything directs and focuses the developers and the practitioners.

In response to these mandatory requirements of legislative obligation, Arup integrated sustainability appraisal into their urban design and masterplanning process and in response to handling the complexities of both processes, responded to the challenges by adapting integrated thinking and developing their IRM innovative modelling tool.

As an overall process, Arup have effectively responded to the legislation by innovatively integrating the processes of urban design, integrated resource management (IRM) and sustainability appraisal for better design practice. The overall approach is brought together by a concurrent effort to specify the objectives that are measurable but also relevant to each of the processes. As such this provides a clear brief and clear design criteria, key performance indicators (KPIs) relevant to IRM and objectives that are set into a sustainability appraisal framework (SAF).

In note of objectives, aspiring environmental and equivalent sustainability objectives are not always at the behest of the customer or priority of the business. As seen in the previous study reported in the previous setion, legislative compliance was often only met with minimum compliance. However, when Arup handled their objectives, it was seen that a range of aspirations that were classified as baseline, target or stretch, were formally offered. In doing so, it encourages the emergence of potentially different design strategies which can expand the design process for the better.

8.4 Chapter Conclusions

This chapter has presented two industry-based case studies to which constraint-based thinking has been applied.

It has demonstrated how product-related and process-related legislation and statutory requirements, when simply considered equivalent to constraints, are not a hindrance and positively stimulate designing processes.

Chapter 9

Constraint-based Thinking: Translating Designing Towards Constraints

"If you don't like something, change it. If you can't change it, change your attitude" - Maya Angelou.

The premise presented within this chapter is based on the case study previously presented by Liang et al. (2008) with respect to, "A Constraint-based Approach to Sustainable Design and Development". This chapter begins by re-emphasising the influence of sustainability in designing and then goes on to demonstrate that when constraint-based thinking is applied, designing problems can be simply translated into constraints, and so that constraint handling methods might be applied.

9.1 The Influence of Sustainability and Sustainable Development in Shifting the Patterns of Designing

This section re-emphasises the impact of sustainability, its interdisciplinary nature, and the consequent process of sustainable development. It discusses the sustainability appraisals that have become inherent and the role of objectives and key performance indicators also respectively integral, but significant in all cases of designing or instances of problem solving.

9.1.1 A Perspective of Sustainability's Interdisciplinary Nature

The Brundtland Report (WCED, 1987) and its influence in sustainability issues has encouraged respective models to be created, which have often been based upon the elements collectively known as the 'triple bottom line'. However, as in Chapter 5, this thesis has since identified sustainability to be more closely related the the elements of 'people, planet, profit, and policy'. Process deemed as sustainable development that features the inclusion and achievement of sustainability elements, has led a shift in patterns of designing and to 'sustainable design', that by nature, is inherently optimisation in a designing context.

The Naturally Arising Complexities of Interdisciplinarity in Sustainable Design

Liang et al. (2008) supports the interpretation of designing as the *"organisation and management of people and the information they develop"* (Ullman, 1997, p.7). The fervent integration of the four sustainability elements, in sustainable design and even in designing in general, means a significant increase in designing considerations that must therefore be made. This is directly affected by the many interdisciplinary influences that need to be negotiated in search of optimal outcomes. With regards to designing process, this means the 'organisation and management' of invariably increased volumes in information.

The interdisciplinary nature inherent to sustainable design and the interaction of four elements as specialist streams that are very established within their own right, naturally gives rise to complexity. As in Chapter 5, complexities are considered to arise under the contexts summarised by 'people, practice, and precendence'. With respect to existing practices, these are very much governed by regulation, for example, the requirements of legislation and statutory requirements. This has been especially dominant in the development of sustainability appraisal in which measuring sustainability and the impact of decisions made is of importance.

Sustainability Appraisals Inherent to Sustainable Design

With respect to sustainable design, there are no well-known process models, but there has been much development in the methods of sustainbility appraisal (Liang et al., 2008). This has been especially under the influence of constraints in the form of relevant legislation and statutory requirements. Appraisals generally differ from assessments by additionally offering evaluations with respect to value generated and/or quality of performance, and not just a general assessment thereof.

The previous emergence of disciplines such as eco-design are seen as the building blocks and provide much of the underlying theory towards achieving sustainability and towards sustainable design itself. Tools such as life cycle assessment (LCA) or environmental impact assessments (EIA) are interchangeably applied as part of both processes. To the same extent that eco-design is inherently identified with the activity of LCA, sustainable design may be identified with the activity of carrying out sustainability appraisal. Furthermore, not only in sustainable design, but in designing in general, appraisals are considered to be a matter of course, and are based on measures of performance indicators.

The Performance Indicators of Sustainability, Designing, or Otherwise

Performance indicators represent objectives that relate to targets and/or measures of success which stem from requirements of design specification, and are commonly labelled in industry as 'key performance indicators' (KPIs). They are also considered to always be present in sustainability, designing, or more generally, instances of problem solving. In this way, there are limitations which are imposed by KPIs and the respective objectives or requirements they represent. These KPIs then impose constraints upon what is generally allowable, hence, Liang et al. (2008) proposed the idea for constraint-based approaches and general constraint handling towards sustainable design and development that is expanded in the next section.

9.2 Constraint-based Thinking and Translating Designing Towards Constraints and Constraint Handling

This section firstly expands the idea of how instances of designing (as problem solving processes), using constraint-based thinking, are translated into constraints and therefore allow constraint handling. It then describes how constraint-based thinking, in this way, is applicable with respect to the context of integrated resource management (IRM) as an example that is affected by the influences of sustainability, is interdisciplinarity, and complex.

9.2.1 Constraint-based thinking: Translating Objectives and Key Performance Indicators as Constraints

With respect to sustainability, Liang et al. (2008) acknowledge that objectives, their respective key performance indicators (KPIs), and constraints both stem from requirements and are invariably used in appraisal of (sustainability or designing) achievement. Although, constraints in all cases, will naturally arise.

The Impact of Imposed Objectives as Key Performance Indicators, and as Constraints

Limitations imposed by acceptable values of KPIs determine what is allowable and in simple terms, these are constraints which also impose upon what is possible. They can most simply be described as declared restrictions and are both functional and fundamental to design-problem solving processes such as sustainable design.

Imposed objectives embodied by respective KPIs and then translated into constraints are in this way equivalent to each other and the route to a preferred outcome may be developed into a constrained optimisation problem. As a result, any constraint-based approach or general constraint handling may be applied.

A Constraint-based Approach and Constraint Handling Towards Sustainable Design

As reported by Liang et al. (2008), computer-aided design (CAD) tools have in past years provided practitioners with computational support that has provided increased capabilities. In the architecture, engineering and construction (AEC) industry, tools such as building information modelling (BIM) have been of great use in coordinating and integrating design practice. Similarly, constraints might also be modelled.

However they might arise, or whatever objectives and KPIs they might represent, constraints may be regarded as a relationship between parameters. This is to the extent that handling constraints becomes the expertise of the practitioner so that the entire design is not jeopardised by poor decision. With respect to modelling, constraints can be used to model how individual instances of designing interrelate with respect to constraint sets and additional constraints that either emerge or are purposely introduced. This naturally creates a complex system or even a network of constraints that are available for optimisation.

9.2.2 Investigating Constraint-based thinking Towards Integrated Resource Management

In the context of sustainability and sustainable development, introduced in Chapter 7, integrated resource management (IRM) is an emergent means of handling KPIs that account for the inherently interdisciplinary nature of sustainability. As a designing support tool, it has been applied to projects within the built environment as part of masterplanning and urban design projects. They have been greatly motivated by the cause of climate change and sustainable design in general.

Liang et al. (2008) identifies IRM specifically as an approach that positively manages and captures the many complex interactions which lead to the eventual optimisation of KPIs, of which the entire approach is focused around. In some ways, the structure of the IRM modelling tool developed and used by Arup (Page et al., 2008), may be similarly compared to a constraint-based modelling environment.

In general, constraint-based approaches largely seek to improve and optimise towards a preferred solution by dealing with the limitations imposed by constraints. Similarly, with an IRM approach, limitations imposed by KPIs imposes constraints upon what is allowable so that the underlying function of both is somewhat the same. Therefore, an IRM modelling environment and general support of an IRM approach towards sustainable design is seen as an ideal forum for investigation. There exists a feasible application of constraint-based thinking that might form a feasible application of constraint modelling as an additional technique in complementing general IRM methodology. This remains within the remit for improving sustainable design and development that is interdisciplinary and complex. It also adds to the scope of existing knowledge concerning constraint-based approaches that have previously been applied to instances of both conceptual and life cycle designing.

Constraint-based Thinking Towards Arup's Integrated Resource Management

Innovative and leading global firm, Arup who who specialise in services for the built environment, have developed an IRM approach and created an IRM modelling that facilitiates the handling of complex interactions within an interdisciplinary capacity. Also previously introduced in Chapter 5, it functions primarily as form of appraisal and/or optimisation support in designing as part of the masterplanning process. In comparison, a constraint-based approach could function under the same capacity and therefore is an ideal setting for demonstrating how constraint-based thinking enhances designing, in general.

9.2.3 Constraint-based thinking: An Example of Translating Designing Towards Constraints and Constraint Handling

A methodology to support the use of IRM models and the decision making process for masterplanning within the built environment has been created Liang & Birch (2011). It is intended that this methodology exist alongside current supporting models and has the capability to become an integral part of sustainability assessments and other associated appraisals.

Within this, the extraction and analysis methodology (EAM) has been created with the aspiration of enabling the practitioners to better understand and manage the complexity within their assessment models. This is discussed more fully in Chapter 10. The methodology also enables a more efficient and focused approach to design and optimisation. The methodology and the defining activities are summarised in Figure 9-1.

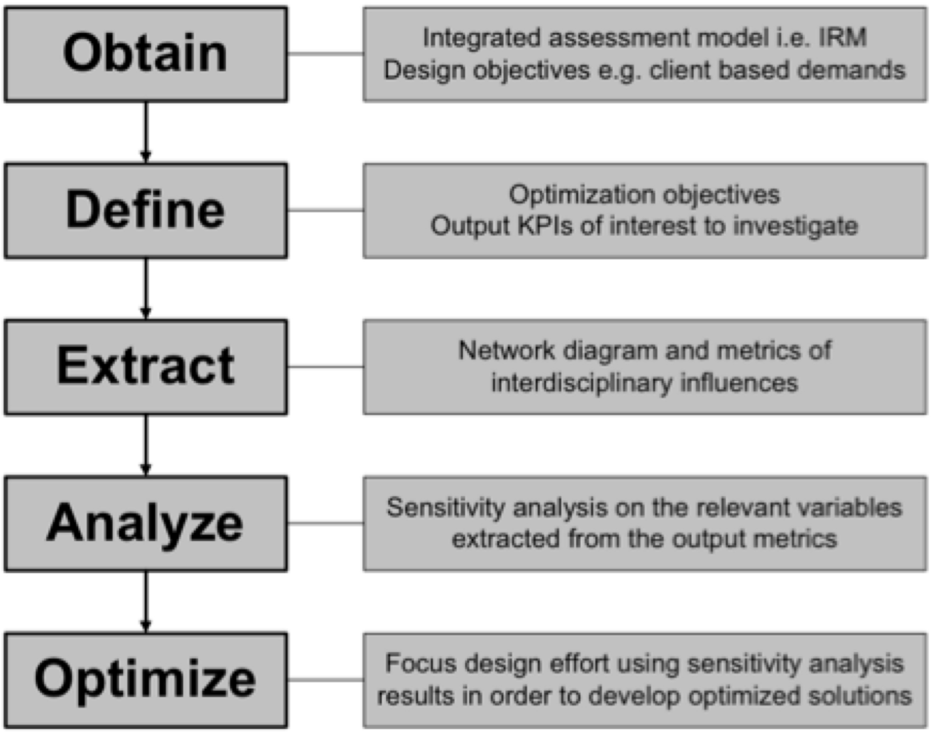

Figure 9-1: Phases of Extraction and Analysis Methodology (EAM) (Liang & Birch, 2011)

In Figure 9-1, the obtain activity is to acquire or set up a constraint system such as the IRM. The define stage is to identify optimisation objectives to which the constraints relate. The subsequent stages are described in the next chapter relating to the created Extraction and Analysis Methodology. Obtain and define are the two main stages that are used in Liang et al. (2008). In the obtain phase, the IRM was identified as the appropriate assessment model. The define stage identified the KPIs as related to issues of sustainability such as land-use, buildings, people, transport, energy, water and waste management. As noted by Liang et al. (2008), techniques of LCA can be used to resolve some of these constraints.

9.3 Chapter Conclusions

In this chapter, key performance indicators (KPIs) were identified as playing a central role to sustainable design and sustainability appraisal. As they impose upon what is allowable, they are fundamentally equivalent to general constraints that are also imposing.

It has been shown that the KPIs can act as objectives within a constraint system, and as such, falls into the remit of constraint-based thinking. Therefore, IRM can be thought of as a instance of constraint-based thinking.

The next chapters consider the question, 'can constraint-based thinking be applied to enhance existing practice of designing and efforts of design thinking in order to support that which is both interdisciplinary and complex'.

Chapter 10

Constraint-based Thinking: Responding to the Challenges of Complexity and Constraints Part 1

"Truth is ever to be found in the simplicity, and not in the multiplicity and confusion of things" - Isaac Newton

The premise presented within this chapter is based on the case study previously presented by Liang & Birch (2011) with respect to, "Extraction and Analysis Methodology for Supporting Complex Sustainable Design". This chapter begins by demonstrating constraint-based thinking can be applied with respect to translating an approach and modelling tool in integrated resource management (IRM) as being a matter of constraints, and of constrained optimisation. It then presents a case study of 'Extraction and Analysis Methodology' (EAM) in which declared optimisation objectives constrain the search for optimal or preferred outcomes. It is a methodology created to explore the interconnections and interrelationships of complex interdisciplinary design that aims to support improved decision making, interdisciplinary understanding, and general handling of complexity.

10.1 Integrated Resource Management as an Example of Constrained Optimisation with Constraint-based Thinking

Applying constraint-based thinking to translate Arup's approach to IRM, and to complement arup's IRM modelling tool, is initially based on the ideas that have been developed by Liang et al. (2008), as described in the previous chapter. The study by Liang & Birch (2011) continues with the context of IRM also previously described but in Chapter 5, and more specifically within the study as sustainable design in the built environment.

This section begins by re-emphasising the importance of understanding not only with respect to designing in general, but for the issues that naturally arise. This is especially with respect to handling and negotiating complexity, expecially in instances of interdisciplinarity in sustainable design within the built environment. It notes IRM and their respective assessments as actively contributing to designing iterations as part of optimisation methods. In addition, this section also describes how applying constraint-based thinking towards integrated resource management (IRM) allows it to be translated into a matter of constraints, and constrained optimisation, and the effects of this.

10.1.1 The Need for Improved Understanding in Sustainable Design as Highly Interdisciplinary and Interrelated Instances

The influence of sustainability has led to the emergence of sustainable design. In addition it has led to an increase in designing tools, supporting methodologies, and appraisal frameworks. However, there is a lack of readily available instruction with respect to managing the extent of complexity which arise in the instances of numerous interrelationships between multiple disciplines and resource streams (Liang & Birch, 2011).

As an aside, it should also be noted that complexity not only arises in instances of sustainable design, but, it is also unavoidable in the supporting tools, methodologies and appraisal frameworks that are created, for they are just as interdisciplinary and interrelated. For example, in the context of sustainable design here, although an IRM approach and modelling tool is applied to support the complex interdisciplinary nature of masterplanning process and has ultimately been successful in doing so, the causes of complexity within both the tool and the process are for the most part, the same. This is of course further to the complexities that inherently arise in the instances of 'people, practice, and precedence' described in Chapter 5.

With respect to Arup's IRM approach, and its IRM modelling tool, there is not only a lack of instruction in managing complexity, but also a lack of transparency with respect to the large number of variables, in the order of thousands, that are handled. Hence, a need has been identified to efficiently manage these and to provide improved designing support to better identify, observe and manage interrelationships, which are equivalent to the means of understanding the problem structure and the design space. This is towards producing optimum scenarios and/or optimal design choices.

Naturally Occurring Optimisation in Arup's Masterplanning Process and Integrated Resource Management

Masterplanning is the entire program of activities associated with respective integrated service provisions for the development of masterplans or urban design. It is a process which is indeed heavily reliant upon the expertise of its practitioners (Liang & Birch, 2011), those of whom commonly use designing support, for example, IRM and its respective assessments and/or appraisals, in order to evaluate the interactions and integration of data captured, and the designing decisions made by all diciplines involved, and their parts of.

With respect to Arup's approach to masterplanning and IRM, the individual evaluations as a result of assessments or appraisals are central to the iterations and measures of designing space that form a natural optimisation process towards an eventual preferred/optimal outcome, and from which pertinent and incremental knowledge emerges. Such optimisation is entirely and fundamentally driven by sustainability objectives that have been declared as part of the masterplan brief and formalisation of a sustainability appraisal framework.

10.1.2 Arup's Integrated Resource Management as a Matter of Constraints and as Constrained Optimisation

The data flows with respect to different resource streams within Arup's IRM model have previously been shown in Figure 7-1 (71). With respect to this, each resource stream shown will contribute a mass of input variables which are then interpreted by the model and evaluated into many different outputs. As specific outputs, they are observed by Liang & Birch (2011) to be interpreted as key performance indicators (KPIs) which can be treated as design parameters, individually represent specific design objectives or part of, and, provide measures of optimality.

Applying Constraint-based Thinking to Integrated Resource Management

With respect to Arup's efforts of sustainable designing in masterplanning and the built environment, and the developed IRM approach based around sustainability objectives represented by KPIs, constraint-based thinking may be applied. As a result, such objectives and KPIs are invariably equivalent to forms of constraints. In this way, Arup's IRM modelling as a supporting tool may then be simply translated as a matter of constraints, and as a process of constrained optimisation. As part of the integrated processes of masterplanning and urban design, integrated resource management, and sustainability appraisal, all previously considered together in Chapter 7 and shown in Figure 7-5, the sustainability objectives that are declared are effectively equivalent to hard constraints that hold a global influence. They are properties of the preferred and/or optimal outcomes that are intended to be achieved. In constrast, KPIs that are specifically used in Arup's IRM modelling and central to its approach, are effectively equivalent to soft constraints that hold a predominantly local influence. The complete IRM model is therefore also a representation of a highly interconnected and interrelated network and/or system of constraints. Such translations in the context of handling objectives as constraints, or even handling constraints as objectives interchangeably, are with respect to constrained optimisation and the different types of constraints also previously described, but in Chapter 3.

Arup's Integrated Resource Management Model as a Framework for Constraint Checking

In the previous chapter, when applying constraint-based thinking, a constraint-based approach was considered to be a potential option that could function in the same capacity as Arup's IRM model. This is in order to handle complex interactions within an interdisciplinary capacity such as sustainable design in the built environment. Hence, both may essentially be reduced to approaches that are constraint-based. As such, Arup's IRM model can form a framework which can be respectively used for basic constraint handling.

With respect to the simpest means of the basic approaches to constraint handling, as described in Chapter 3, Arup's IRM model may be used for constraint checking. In this way, each KPI as a local constraint may be tested in turn using the most current design variables, and any violations may be simply reported. In such instances, constraint checking of quantitative KPIs in the IRM model is useful not only towards assessing the extent of how, but also to whether sustainability objectives as global constraints, have or have not been achieved. In the context of using Arup's IRM model and KPIs as a framework for constraint checking, it offers very little in understanding how the variables in one particular instance might specifically contribute to an iteration in constrained optimisation. That is to say, there is no indication of how the variables interrelate with each other or towards an optimal or preferred outcome. It also offers no indication as to the constraints that exist or might emerge as being significant in the IRM framework itself, at least without careful analysis.

Exploring the Influences of Constraints Equivalent to Optimisation Objectives as a Means of Understanding

In the previous sections of this chapter, applying constraint-based thinking simply translates the declared optimisation objectives of the IRM approach and modelling process represented by KPIs, as being equivalent to forms of constraints. In reality, and in search of optimal or preferred outcomes, there are many more constraints that will invariably arise along with associated conflicts and/or complexity. Furthermore, issues of complexity are further compounded by the interdisciplinary nature of IRM modelling which is just as complex as the masterplanning and sustainable design process which it aims to support. Focusing on the constraints equivalent to optimisation objectives it is possible to explore the extent of their interactions, interconnections, and interrelationships with respect to the influences of the many variables within an IRM model. This would then provide a means of investigating how and where complexities arise with respect to specific constraints. It would also facilitate understanding with respect to interdisciplinary influences of IRM resource streams, overall. Developing practitioner understanding respectful of problem structure or design space would support improved decision making, interdisciplinary understanding and handling complexity towards supporting such sustainable design.

The next section describes the 'extraction and analysis methodology' (EAM) that has been specifically created by Liang & Birch (2011) that supports complex sustainable design by exploring the interactions and interrelations between constrained objectives and their variables in order to faciliate such improvements.

10.2 Extraction and Analysis Methodology (EAM)

Constraint-based thinking has been applied in the context of complex sustainable design in the built environment and translated as an example of constrained optimisation. Considering the example of Arup's integrated resouce management (IRM), this section closely explores the case study of Liang & Birch (2011), and the created extraction and analysis methodology (EAM).

The methodology is a response to the challenges of complexity and constraints focused on declared optimisation objectives that extracts appropriate data and information, and fosters the necessary understanding to reduce complexity through the analysis thereof. This section begins by firstly providing an overview of EAM and then more closely examining its methods and toolkit as activity phases that make up the complete methodology.

10.2.1 An Overview of Extraction and Analysis Methodology

The creation and development of the extraction and analysis methodology (EAM) has been aimed at understanding the interactions, interconnections and interrelationships within the setting of integrated resource management (IRM) in the context of Arup's masterplanning and urban design process. The methodology primarily functions around IRM's key performance indicators (KPIs) that form optimisation objectives. These are then investigated in order to manage complexity with respect to how and where it might emerge, and the consequent handling of such objectives as constraints.

Further to the case study by Liang & Birch (2011), "Supporting Complex and Sustainable Ecocity Design Using Extraction and Analysis Methodology" has also been presented at the Ecocity World Summit 2011, Montréal, Québec, Canada.

The Functions of Extraction and Analysis Methodology

The motivation for the methodology created by Liang & Birch (2011), can be simply summarised by its three fundamental functions, described in the following list.

- Exposing how and where complexity arises, and its handling thereafter, through more transparently demonstrating the interconnections and interdependencies of integrated data.
- Facilitating increased understanding with respect to specified optimisation objectives and towards more desirable and/or ideal scenarios generating optimal/preferred outcomes.
- Gaining increased knowledge, incrementally and iteratively or othewise, with respect to how adjusting sets of variables may better contribute towards the final optimal/preferred outcome.

The Activity Phases in Extraction and Analysis Methodology

Figure 10-1 shows a general overview of EAM which consists of the activity phases, 'obtain', 'define', 'extract', 'analyse', and 'optimise'. The methodology itself can more generally be split into two parts with respect to extraction and analysis.

In the 'extraction' part of the methodology, pertinent information related to establishing and specifying design intentions is firstly obtained from a design brief along with an assessment (and/or appraisal) framework. In order to conduct the EAM investigations, the scope is defined with specifically selected optimisation objectives.

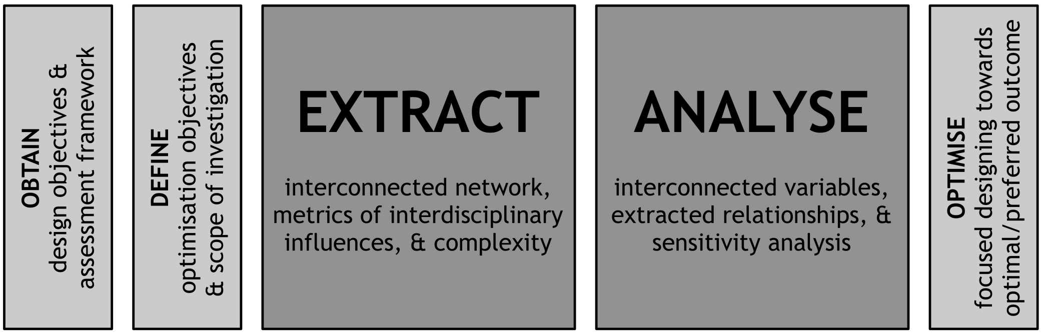

Figure 10-1: A General Overview of Extraction and Analysis Methodology (EAM)

These initial phases in the methodology very much influence the extraction of metrics, interdiciplinary influences and extent of complexity. In the 'analysis' part of the methodology, the extracted data and information that emerges from extraction is analysed. A sensitivity analysis is then carried out as a further assessment to garner understanding fundamental towards the overall aim of achieving the previously extracted optimisation objectives. In addition to the general overiview provided in this section, the following sections provide more detailed descriptions of each activity phase.

10.2.2 Obtain: The Set-up Required for Extraction and Analysis Methodology

With respect to the activity phase 'obtain', there are two main actions required. The first action is to obtain the designing objectives that drive EAM, and the second action is to obtain an assessment framework which EAM can then be applied to. Both actions are equally important and are fundamental to setting up the EAM.

Obtaining Design Objectives for Driving Extraction and Analysis

The design objectives used to drive EAM are equivalent to the demands by the clients and/or stakeholders, relevant legislation and statutory requirements, and, the design brief. Therefore, they are easily obtained as well as being absolutely neccessary for EAM. In some instances, it may also be possible to obtain the same objectives from an assessment/appraisal framework which is also necessary for the obtain activity phase.

Obtaining a Framework for Applying Extraction and Analysis

In 'obtaining' an integrated assessment or appraisal model, a framework for applying EAM is provided as a forum with which practitioners may work with. In general, these allow investigation of 'potential solutions, different cases or scenarios and initial conditions or design boundaries' (Liang & Birch, 2011). Furthermore, it is noted that such frameworks can be used throughout the designing process, or just as commonly, in singular parts thereof. This would be with respect to diffrent phases, for instance, in design-problem solving. Similarly, this is the same for EAM and it may also be applied at any phase of designing or optimisation. However, both are considered to be most effective when used earlier on.

With respect to the case study by Liang & Birch (2011), Arup's integrated resource management (IRM) model, previously described in Chapter 7, has been used as the example framework for applying EAM. It is an example of a model that is highly interdisciplinary and complex itself, and in fact along with its integrated masterplan brief and sustainability appraisal framework (SAF), it is indeed possible to obtain design objectives that have been incorporated into its structure.

Although it has been proposed that general integrated assessments may be equally created as opposed to obtained, it is strongly noted, based on the nature of Arup's IRM model, creating anything similar would be quite a substancial effort for those opting to prescribe to EAM. However, it is also feasible that different integrated assessments may be equally adapted into a suitable form, and as opposed to being built from scratch.

10.2.3 Define: Optimisation Objectives for Constrained Optimisation with Extraction and Analysis Methodology

The output of KPIs within the example of Arup's IRM are forms of optimisation objectives equally used in EAM's activity phase, 'define'. In the activity phase of defining, when declared as key performance indicators of interest (KPII), EAM is used to investigate their respective interconnections and interrelations. In this way, these objectives are subjectively selected to investigate a particular line of inquiry. They also significantly impact upon the contributions towards and direction of optimisation using EAM.

10.2.4 Extract: The Interconnections and Interrelationsips Towards Better Understanding the Design Space

In the activity phase 'extract', the aim is to gather and disseminate understanding relevant to exposing the extent of complexity and the overall integrated scope of the design space in an interdisciplinary context. This is with respect to a specific key performance indicator of interest (KPII) through the extracted interconnections and interrelationships that occur between the variables, and how they themselves might therefore be constrained. The rationale for each extraction as metrics and/or matrices are discussed in the following sections.

Extraction of Interconnected Network of Variables

As part of the complete extraction, the interconnections of all involved variables are visualised graphically using a GraphML format so that the full complexity and integrated scope relevant to a KPII may be instantly demonstrated (Liang & Birch, 2011). The visualised interconnections effectively offer an insight into an instance or snapshot of the design space and with respect to the structuring of data variables.

Extraction of Variable Count and Distribution (VCD) Metric

In relation to a specific KPII, this metric provides information regarding the total number of variables and their distribution or, how they are connected to each other. This is with respect to their frequency within the assessment/appraisal framework, but also to their 'discipline of origin' and therefore the resource stream to which the variable is relevant to.

Effectively, this metric is a measure that demonstrates complexity simply through the volume of variables and the volume of variables that emerge from each discipline and/or resource stream.

Extraction of Independent Variable Count and Distribution (iVCD) Metric

In relation to a specific KPII, this metric provides information regarding the total number of independent variables and their distribution, but with respect to their frequency and discipline of origin. This is in the same capacity as the more general variable count and distribution metric but specifically for 'independent' variables. Hence, this metric is a measure that demonstrates complexity simply through the volume of variables whilst also considering their context. It is noted that, independent variables are inputs that are not a function of any other variable within the system that is being modelled, and dependent variables are those that are a function of one or more variables present within the same system.

Extraction of Reference Count and Distribution (RCD) Metric

In relation to a specific KPII, this metric provides information regarding the total number of connections made between different variables or, how they refer to each other as a series of references. This is with respect to the number of references made between each of the variables and also its the discipline of origin. Effectively, the metric is a measure that demonstrates complexity through the volume of interconnections that emerges within the assessment model.

Extraction of Direct Reference (DR) Matrix

In relation to a specific KPII, this matrix provides information from each variable of a particular discipline and how it is connected with respect to the complete distribution of connections or rather references that are made to all other disciplines. Effectively, the matrix aims to demonstrate complexity by the extent of interconnectivity between different disciplines and therefore through the volume of direct connections.

Extraction of Independent Direct Reference (iDR) Matrix

In relation to a specific KPII, this matrix provides information but from each 'independent' variable of a particular discipline and how it is also connected with respect to the complete distribution of connections or, the references that are made to all other disciplines. Effectively, the matrix aims to demonstrate the extent of interconnectivity between independent variables and different disciplines through the context of direct connections.

Extraction of Indirect Reference (IR) Matrix

In relation to a specific KPII, this matrix provides information on how each variable of a particular discipline is connected in any way, to another. This is again with respect to the complete distribution of connections or, the references that are made to all other disciplines. Effectively, the matrix aims to demonstrate the extent of interconnectivity between all the variables and all the different disciplines. The context of complexity here is simply demonstrated through the volume of all connections made.

10.2.5 Analyse: Evaluating Assessment of Extraction and Application of Sensitivity Analysis

The activity phase 'analyse' further builds upon the extracted independent variables and the analysis of, and still with the aim of providing support towards decision making and directing improved optimisation efforts. This is through a robust assessment of impact by applying sensitivity analysis upon the parameters and variables involved (Liang & Birch, 2011). As such, it is driven by its function to help determine how various input/outputs of an assessment model might predominantly respond. Depending on changes and/or constraints that are imposed upon specific variables, this makes it possible to determine which ones are likely to hold more dominance, and therefore how they might contribute to a KPII.

The rationale, necessary preparations, and post-processing in sensitivity analysis of extracted independent variables as part of EAM in general, is discussed in more detail in the following sections.

Analysing Towards Designer Illumination

Applying sensitivity analysis demonstrates which variables hold more dominance and their interaction with respect to those that are most sensitive to changes of. Iteratively carried out, this develops and increases designer knowledge and understanding, all related to the overall responsiveness regarding specific input-output variables and where an impact of change may most likely effect achieving optimal/preferred outcomes.

Analysing Towards Reducing the Design Space

Sensitivity analysis may also be applied in order to evaluate which variables lack dominance to the extent that it is possible to reduce part of the problem and/or the design space. By testing proposed assumptions as imposed constraints, variables may be tested as being either effective or otherwise, and potential conflicts of input-output variables may also emerge. Its impact would then support reducing the design space, again in achieving optimal/preferred outcomes.

Analysing Towards Focusing Design Effort

By facilitating designer illumination and reducing the design space, the application of sensitivity analysis fundamentally shows the (EAM) prescriber where to focus design effort. This is by directing them towards the specific areas that are most relevant, and hence the variables that have the scope for most impact. Essentially, such analysis is another means of building an understanding but in how the data is connected, where it is most connected, and how it might have the most impact.

Preparations for Sensitivity Analysis

For a sensitivity analysis, there are necessary preparations that must be made in order to faciliate investigations with respect to the assessment/appraisal framework obtained and appropriately managing the independent variables extracted. These are listed as follows.

- **An Interpreted Description**
  This may not be necessary for all frameworks obtained, or in every instance of sensitivity analysis. However, an interpreted description or an easily identifiable label is simply useful to add as an inclusive interdisciplinary aspect. Hence, it is for the benefit of practitioners that might handle sensitivity analysis data/information.

- **A Specified Default or Test Value**
  This is a specific value for each variable, used to set-up the scope of an interation in sensitivity analysis that should be 'relevant and realistic'. However, such a value may be zero or even estimated. Most commonly, it would be either an assumed/default value, or an initial/test value which is decided and based upon assumptions of a practioner and in the context of the general aims of sensitivity analysis.

- **A Specified Confidence Interval**
  The confidence interval simply constrains each independent variable with a maximum or minimum value that adds further context to the analysis. This is in addition to the default or test value and to also appropriately direct the scope of investigation.

Post-processing and Results of a Sensitivity Analysis

Once the sensitivity analysis has been applied, the results are normalised from absolute values and rated on a scale of zero to one-hundred. The general shape of the results must then be interpreted by a practitioner to assess whether there are indeed any variables or even a group thereof, that may or may not be particularly dominant towards a KPII.

The sensitivity analysis provides an insight into the independent variables that are most sensitive to changes with respect to a specific data set and/or iteration of optimisation. As a result, any independent variables exposed as having a dominance towards a KPII and hence significantly contributing to an optimisation objective, can be taken advantage of. This is with respect to focusing the design effort and reducing the investigated design space since dominant variables are seen as influential towards increasing efficiency of design iterations with respect to a KPII and/or optimisation objective.

As a caveat, prescribers of such a sensitivity analysis should note that there may be a point at which many or all variables have similar sensitivity values. Therefore, it may not be practical to interpret these with any understanding as it becomes difficult to differentiate them from potential aliasing effects. Furthermore, it is noted that sensitivity analysis reveals very little with regards to interaction between variables.

10.2.6 Optimise: Constrained Optimisation With Extraction and Analysis Methodology

Using EAM, design optimisation is supported by concentrating on one key performance indicator of interest (KPII) and then exposing and managing associated complexity to understand how an appropriate design space might be optimised. That is to say, the efficiency of optimisation is increased by constraining with respect to a KPII and investigating the consequent constraints and impacts thereof.

Using optimisation objectives in this way also involves more manageable data sets that are more useful in eventually disseminating understanding for the sake of the practitioners involved when concerning optimisation of an entire design space in general. Although design optimisation is fundamentally supported with the methods in both extraction and analysis parts of the methodology, it is also possible that when KPIIs are handled directly as constraints, further optimisation techniques such as direct search and/or gradient methods might be applied (Liang & Birch, 2011).

10.2.7 Results of the Case Study

Liang & Birch (2011), using the created extraction and analysis methodology (EAM), applied the tools and techniques to a case study which considered an eco-city masterplanning development for the scenario of a highly populated urban area of 7,500,000 square metres.

An IRM model was created for the study which modelled a series of KPIs and provided an integrated assessment of a design scenario based on inputs from several technical disciplines. As noted previously, the IRM model is composed of the constraints which underly the designing task. As a performance indicator, the KPI representing carbon emissions was selected as that of interest in the study. The results are presented in the following tables.

Metric Details / Description	Count	Percentage Distribution of Metric Data (%)					Most frequently used variable
		landuse	transport	water	energy	other	
Variable count / distribution	2357	2	30	16	40	12	1. energy demand 2. water demand
Independent count / distribution	1117	2	25	17	41	15	1. energy demand 2. residential land
Reference count / distribution	3404	3	8	5	17	N /A	N /A

Table 10.1: Extraction of Variables (Liang & Birch, 2011).

Table 10.1 shows the results of the extraction on the variables within the case study model. These represent a selection of the results for four key disciplines of landuse mix, transportation, water management, and energy consumption. All other disciplines are grouped into the last section for percentage distributions of the variables.

Table 10.2 (p.107) demonstrates the percentage distribution of the total number of references made from one discipline to another directly, whilst Table 10.3 (p.107) demonstrates the same distribution for independent variables.

Table 10.4 (p.107) demonstrates the distribution of the total number of references made from one discipline to another indirectly. The total number of references is listed in the left hand column of each reference matrix and the same disciplines are reported as in Table 10.1 (p.106).

Percentage Distribution of Direct References (%)	from\to	landuse	transport	energy	water
	landuse	0.5	0	2	0.4
	transport	0	29	2	0
	energy	0	0	37	0
(3404)	water	0	0	0.1	16

Table 10.2: Reference Matrix of Direct Variable References (Liang & Birch, 2011).

Percentage Distribution of Independent References (%)	from\to	landuse	transport	energy	water
	landuse	8	0	1	4
	transport	0	24	2	0
	energy	0	0	25	0
(1516)	water	0	0	0	12

Table 10.3: Reference Matrix of Independent Direct Variable References (Liang & Birch, 2011).

Percentage Distribution of Indirect References (%)	from\to	landuse	transport	energy	water
	landuse	< 0.01	0	1	< 0.01
	transport	0	< 0.01	0.4	0
	energy	0	0	28	0
(41,068,458)	water	0	0	10	< 0.01

Table 10.4: Reference Matrix of Indirect Varibale References (Liang & Birch, 2011).

The results from the extraction indicate that energy as a discipline contributes the largest number of variables towards the KPI of carbon emissions. The energy demand variable from this discipline is also most referred to within the assessment model as well as being the most frequently used in calculating an assessment for total carbon emissions. The frequency of the water demand variable and residential land variable in total independent variables also demonstrates that these are particularly involved in calculations for carbon emissions.

By extracting the total number of references, this may be considered as a direct correlation to the complexity that is handled within each discipline for the specific output KPI of carbon emissions. It also demonstrates the capability of the IRM model to efficiently manage a large number of interlinked and complex variables in order to support design decision making.

From the generated extraction metrics, the list of independent variables was carried forward for use with the sensitivity analysis tool. Alongside the distribution of variables and the most frequently used variables, the sensitivity analysis provided a perspective on the variables that hold the most dominance.

Technical Discipline	Distribution of Variable Dominance (%)		
	High	Moderate	Low
landuse	17	41	42
transport	2	68	30
energy	12	62	26
water	4	81	15

Table 10.5: Sensitivity Analysis Distribution of Dominance (Liang & Birch, 2011).

Table 10.5 provides an indication of the percentage of variables that have a very high, moderate, and low dominance with respect to the disciplines previously detailed. These results then provided a design focus in which those variables that demonstrated a high dominance were examined more closely in an effort to optimise the KPI for carbon emissions and further understand their influence.

10.3 Chapter Conclusions

This chapter has demonstrated that by applying constraint-based thinking, integrated resource management (IRM) is indeed an example of constrained optimisation that presents challenges of a highly interdisciplinary and complex setting.

This chapter has explored the activity phases of extraction and analysis methodology (EAM) that have been created in response to such challenges. It is concluded that the methodology is indeed effective. Overall, EAM supports improved decision making, interdisciplinary understanding, and general handling of complexity. In particular, a specific case study has been given in which the IRM was used to help optimise a carbon emissions performance indicator.

The next chapter explores how the methodology seeks to gain understanding with respect to the interconnections and interrelations of variables and/or parameters, and their relationships, specifically towards a defined optimisation objective.

Chapter 11

Constraint-based Thinking: Responding to the Challenges of Constraints and Complexity Part 2

"The connections, the connections, the connections. It will in the end be these details that give the product its life" - Charles Eames

The premise presented within this chapter is based on the case study previously presented by Birch et al. (2013) with respect to, "Multidisciplinary Engineering Models: Methodology and Case Study in Spreadsheet Analytics". This chapter begins by exploring the need for models that bring together multiple disciplines in sustainable development as a result of sustainability's impact. It considers the complexity of those implemented in spreadsheets for their ease of construction, and as motivation for spreadsheet analytics. This chapter then demonstrates how extraction and analysis methodology (EAM) has been applied to integrated resource management (IRM) as a real example of spreadsheet-based modelling that involves multiple disciplines, is interdisciplinary, and especially affected by complexity.

11.1 Multiple Discipline Spreadsheet-based Modelling: Easy Construction to Challenging Complexity

Birch et al. (2013) note that multidisciplinary models are in many cases, implemented within spreadsheets because of their easy 'construction, modification and portability', but also for their capability in realising benefits of integrated modelling. This section begins by exploring the need for these multiple discipline or multidisciplinary models that have indeed been implemented as spreadsheets and uses a real example of integrated resource management (IRM) with real data points as the scope for investigation. It then discusses the implications of spreadsheet-based modelling and the specific challenges and/or constraints that arise as motivation in search of improvements.

11.1.1 Exisiting and Implemented Spreadsheet-based Modelling in a Case Study of Integrated Resource Management

As a result of the increasing vigour, in response to the concerns of sustainability and hence, in the context of sustainable design, there is a demand for modelling that is especially considerate of the multiple disciplines that must work together and are involved, but not limited to, the general designing and planning processes of the built environment. This has been seen in examples of integrated resource management (IRM).

Arup's Integrated Resource Management as an Example of Real Spreadsheet-based Modelling

Birch et al. (2013) uses Arup's IRM model as an example that consists of, but also integrates multiple discipline specific sub-models that are relevant to respective resource streams including land-use, waste, energy, carbon, passenger-transport, and water. Of these streams and their equivalent sub-models, they are implemented within a spreadsheet-based modelling environment. In Arup's IRM, for discipline specific data that is collected and/or processed thereafter, there is a specfic input-model. The data within each of these is managed in their own respective worksheet and then paired with another, an output-model, that evaluates values based on a series of applied calculations. These are further connected to a project dashboard or summary-model that contains the assessment of the complete project using key performance indicators (KPIs) as its metrics. An example being energy demand per annum contributing to total carbon emissions. The summary-model also connects to sustainability objectives and shows whether or not they have been achieved.

For each discipline or resource stream, the many input-model to output-model pairings are not only strongly reliant upon each other, they are equally reliant upon the pairings or rather connections that also occur between other disciplines and their respective pairings. As an example, the sub-model of energy supply pairs with data variables from a land-use input-model and an energy demand output-model. As a result of these interconnections, this creates an especially complex and interrelated network of sub-models that indeed reflect the nature and interdisciplinarity of sustainability itself. In this case of spreadsheet-based modelling, it is to the many challenges that arise which provide motivation to make improvements in response to (Birch et al., 2013).

11.1.2 The Challenges Arising and Motivating the Improvements in Spreadsheet-based Models Towards the Multiple Disciplines of Arup's Integrated Resource Management

Birch et al. (2013) have studied Arup's IRM as an example of spreadsheet-based models that are easy to construct. In general they do not necessarily require formal programming experience of model development, and are implemented based on their easy modification and portability. For example, Arup's IRM is connected to databases of geographic information systems (GIS). However, it is acknowledged that there are specific challenges that arise with respect to the integrated nature and multiple disciplines involved, and these are motivation for improvement. They are discussed, along with their implications, in the following sections.

The Challenges and Implications of Complexity and Interdisciplinary Pratice

In bringing together multiple disciplines in an integrated platform, complexity inherently arises in Arup's IRM, not least of all, due to the connections between input-model and output-model pairings of one discipline, but to multiple disciplines. In addition, the sheer volume of all connections, in the order of thousands, between relevant data variables, affects the understanding of the interconnections and the functions in modelling individual disciplines or resource streams themselves. That is to say, there is difficulty in observing instances of cause and effect as a result of such integration. Furthermore, with such interdisciplinarity, lack of understanding in such models especially presents difficulties to practitioners who are working in the context of a discipline or resource stream, not necessarily within their usual remit and area of expertise.

The Challenges and Implications of Data Requirements

For the multiple disciplines involved, and simply with respect to the scale of masterplanning and urban design, there is a significant demand in data required. The time and effort necessary to gather relevant data that must also be processed into an appropriate format, then becomes a cost in applying such models. In addition, according to the extent of complexity and model structure, these models are not always entirely coherent until the input-models and respective output-models are completed with a sufficient level of relevant data.

The Challenges and Implications of Knowledge Representation

Arup's IRM model is an attempted facsimile of the real life interconnections relevant to sustainability measures of a particular instance, or, a specific masterplanning and urban design project. In this way, it is an aggregated repository not only for respective data variables, but also for the knowledge in how these are interrelated. Such knowledge, continually acquired as part of professional practice over time, is difficult to formalise. This is especially within the limitations of the functions available in spreadsheet-based modelling.

The Challenges and Implications of Model Adaptation Specifically for Individual Instances of Masterplanning and Urban Design

More often than not, projects in masterplanning and urban design present individual instances that require a unique approach. As a result, their models often require adaptation to better fit their purpose of use. In some instances, the IRM model may be too broad as some sub-models might not even be relevant. In addition, in the earlier stages of a project, the broadness of IRM models and their excessive data requirements may prove to be especially challenging and cause issues of complexity to arise. In contrast, IRM models may also be too narrow and lack the sub-models necessary for particularly niche scenarios, or very specific design demands. For completeness, these must then be created and integrated into the existing model. In both instances, since cause and effect is not easy to ascertain because of the IRM model's highly interconnected nature, adaptation can prove to be difficult. This is especially when attempting to ensure that changes in the model are consistent with all existing interrelationships.

Furthermore, whilst it has been said that manipulation of spreadsheet-based models is an advantage, there is a caveat in which its portability means that it can be too easy to make changes of varying effect. Without careful mediation and tracking of such changes, it would later be impossible to assess the impact of, or even re-call changes made. In this way and with respect to the scale of modelling, errors are likely to emerge.

The Challenges and Implications of Implementing Spreadsheet-based Models in Instances of Design Optimisation

Implementation of the spreadsheet-based IRM model is commonly part of evaluating instances of design optimisation and towards an optimal/preferred outcome. However, it is necessary for IRM modellers to understand not only the entire overview that includes all the multiple disciplines involved, but also the nitty-gritty details of each. This includes their respective sub-models, and the input-model and output-model pairings. Lack of specific knowledge and understanding at different levels or points in the process means that opportunities might be overlooked or discovered in a less than timely manner.

11.2 Extraction and Analysis Methodology Towards the Spreadsheet-based Modelling of Arup's Integrated Resource Management

In response to the challenges and implications discussed, help to expose, reduce, and manage complexity in Arup's spreadsheet-based IRM model has been supported by applying the extraction and analysis methodology (EAM) created by Liang & Birch (2011). As a result, many insights have been generated and the value of the methodology as support towards design understanding and focusing efforts of design optimisation are demonstrated in the following sections that report from the respective case studies of both Liang & Birch (2011) and Birch et al. (2013).

Figure 11-1 shows a summary of the activity phases relevant to the case study carried out in collaboration with Arup in which the EAM is applied to IRM modelling.

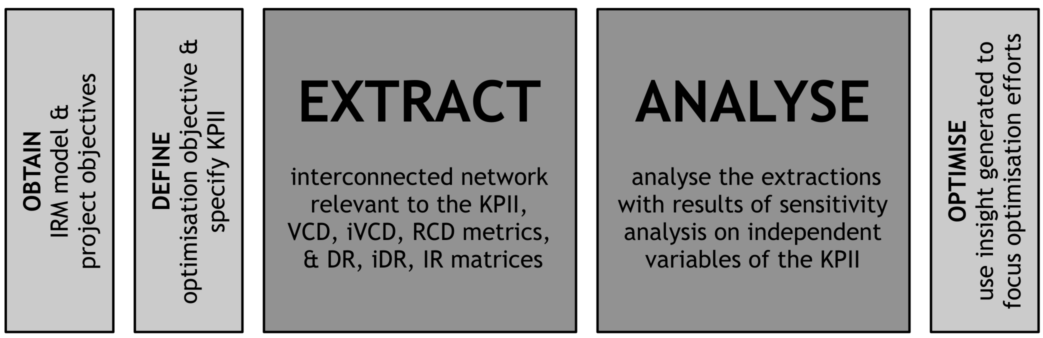

Figure 11-1: Applying Extraction and Analysis Methodology Towards Arup's Integrated Resource Management Model.

The case study of which the results are reported in the remainder of this chapter are specific to a (confidential) project for an eco-city masterplanning and urban design development of a highly populated urban area of 7,500,000 square metres.

11.2.1 Applying Extraction and Analysis Methodology, and the Obtain and Define Activity Phases

In applying EAM, as part of the 'obtain' activity phase, a number of IRM models were obtained from Arup, along with their specific project objectives. These objectives were incidentally already defined within the IRM model and also within an adjoining sustainability appraisal framework (SAF) that was also connected to the IRM model. With respect to the 'define' activity phase of EAM, key performance indicator of interest (KPII) relating to total annual per capita carbon emissions was defined as the optimisation objective. In this thesis, it is henceforth simplified to total carbon emissions.

11.2.2 Applying Extraction and Analysis Methodology, and the Extractions of the Extract Activity Phase

With respect to the defined optimisation objective and the KPII of total carbon emissions, the first action of the next activity phase was to 'extract' a slice of the model so that only the relevant variables, or cells in the spreadsheets, are considered. Slicing of a model (or computer program) is a well-known technique that was carried out by recursively extracting the variables. It used the KPII as the starting point, searched and parsed for references to other variables, and did so until there were no more. As part of the process, individual variable descriptions were also extracted with respect to the cell label or its default name and the values within them. The result of slicing as the extraction part of the methodology is an interconnected network that was visualised, and from which metrics and matrices demonstrating interdisciplinary influences were automatically calculated. Part of this extraction also eventually contributed to the preparations necessary as part of the sensitivity analysis performed later on.

Extraction of the Interconnected Network for the Variables Connected to, and the Interconnections for Total Carbon Emissions

As part of the methodology, the extraction of the interconnected network was presented as a calculation graph. As a simple visualisation of a model slice in the context of the defined KPII, data variables were represented by nodes (data points), and the references made between such variables were then represented by the edges of the graph (connecting lines). Each node was distinguishable from its discipline of origin by being labelled accordingly and also differently coloured.

Figure 11-2 (p.114) demonstrates the results of the extraction for the interconnected network of over nine-hundred data variables, with respect to the total carbon emissions of the 7,500,000 square metre eco-city case study. Although the content of this figure does not present the extractions's variables (nodes) and references (edges) in a discernible manner, it serves to visually demonstrate the real extent of complexity which occurs.

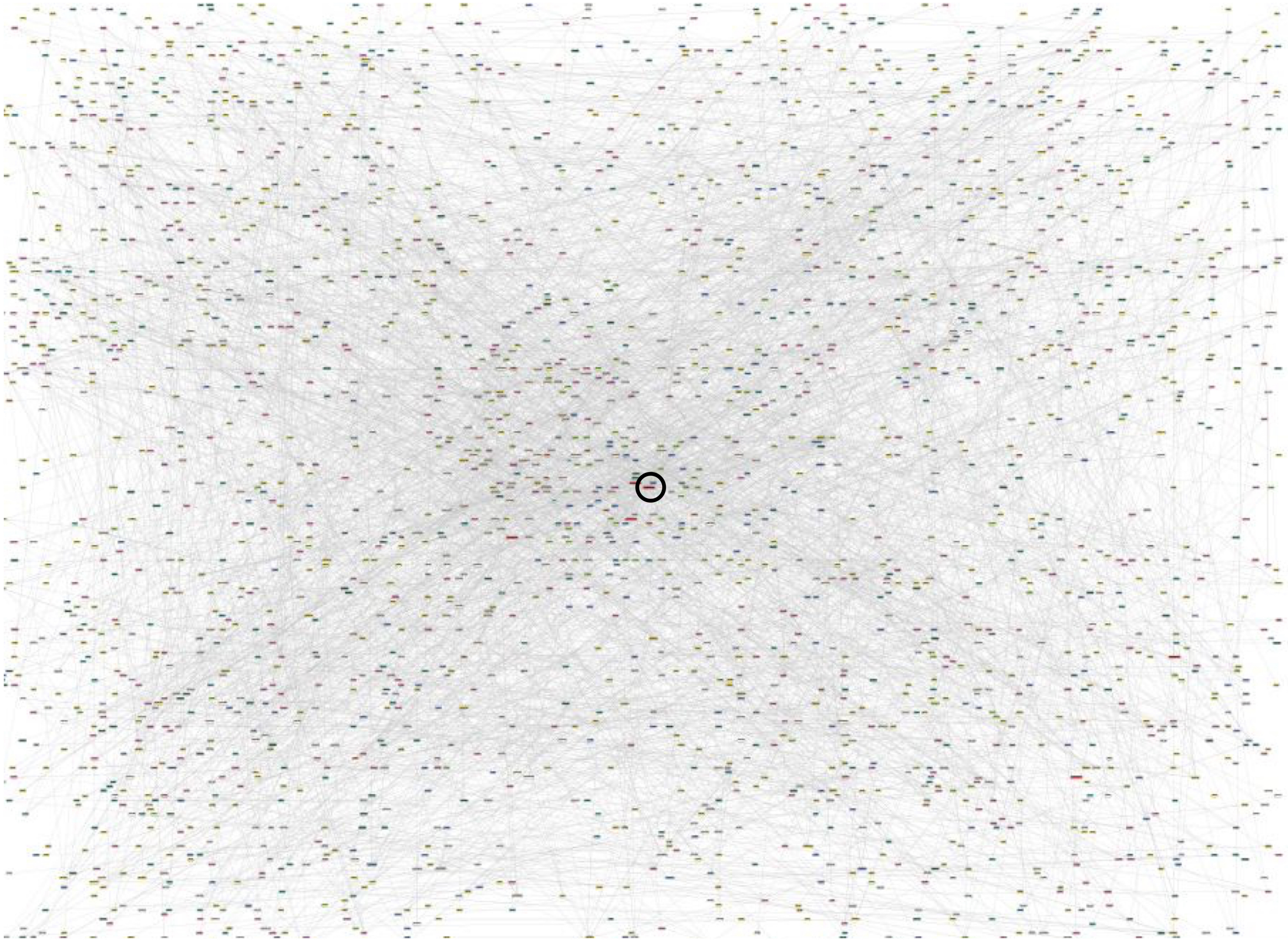

Figure 11-2: The Complete Network of Interconnections with Respect to Total Carbon Emissions of the Eco-city Case Study.

As seen in Figure 11-2 the instance in which complexity was overwhelming, further slicing or extraction of sub-models and sub-calculations was considered necessary. This was so that a more manageable approach to exploring the design space and hence, handling complexity, was possible as part of the methodology.

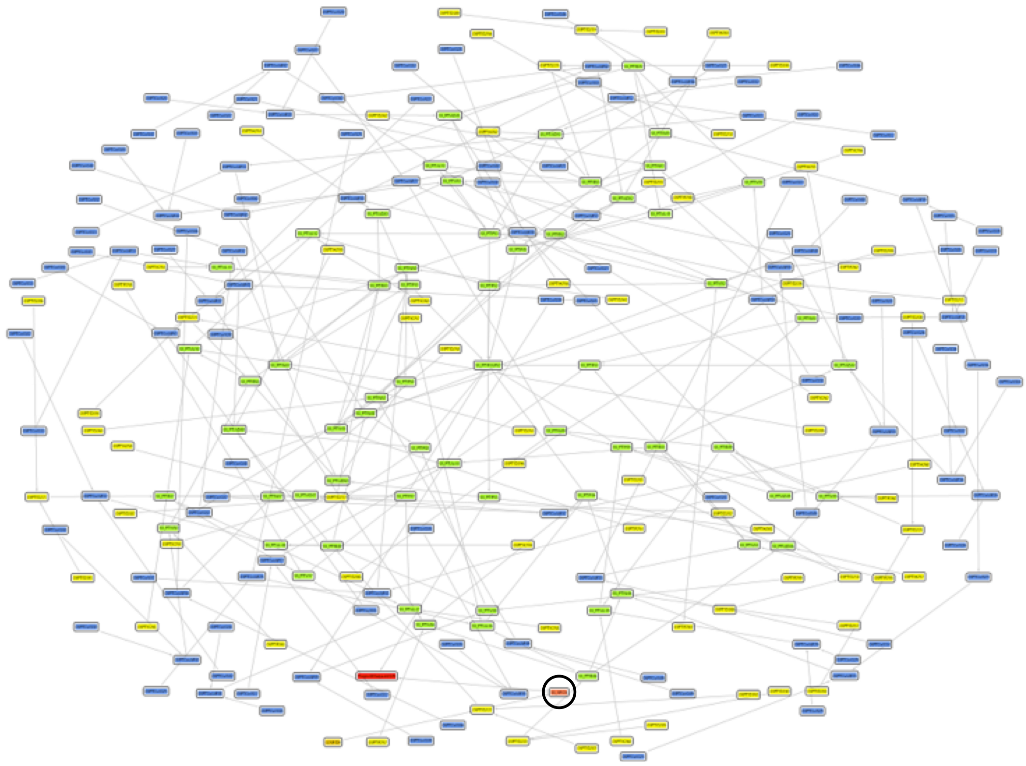

Figure 11-3: An Interconnected Network as a Visualisation of an Extraction (expanded from the circle in Figure 11-2).

A more discernible example of a graph calculation, and the respective visualisation of an extraction, can be seen in Figure 11-3. It shows the nodes as variables from three different disciplines of origin using the three colours blue, green, and yellow. The singular red node represents the key performance indicator of interest (KPII) and the orange node is another key performance indicator (KPI) not specifically related to the optimisation objective in this instance, but that is nonetheless connected.

In this way, model slicing as part of extraction specifically constrained by the choice of optimisation objective and KPII means the extent of complexity can be significantly reduced. As a result, it is easier for a practitioner, familiar or otherwise to the IRM model, to gradually build their knowledge and understanding of the complete or more complex interconnected network. It also allows for more manageable instances of designing and iterations that contribute to optimisation. Furthermore, visualisations of calculation graphs can also be used to explore the structure of a model so that its construction might be tested, and in order to avoid the instances in which errors, although likely, will occur.

With respect to the eco-city case study, Figure 11-4 shows the visualisation of a calculation graph for a sample extraction. This has been for the KPII of total annual per capita carbon emissions for external transport which contributed to the optimisation objective related to total carbon emissions. In the figure, the ten different clusters of nodes each represent ten different sub-models. These are the inputs which are connected to the KPII that is located within the much smaller, central group of nodes. The connection of the two clusters in the right of the figure was in fact an anomaly as there should have been no interconnection between any of these sub-models.

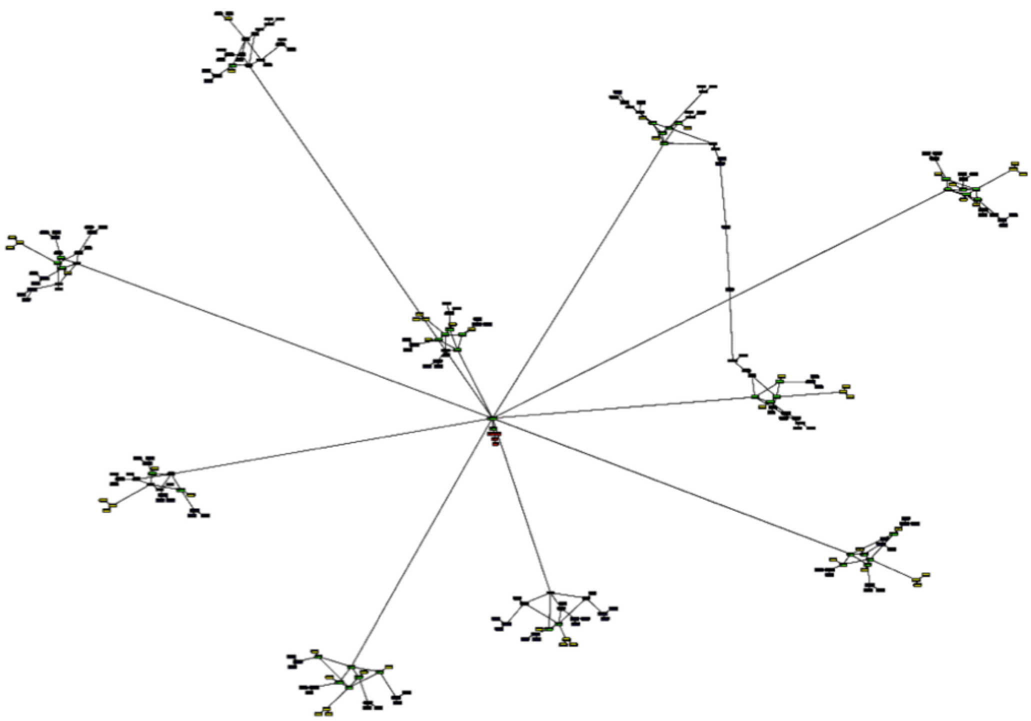

Figure 11-4: An Interconnected Network as a Visualisation of a Smaller Extraction (expanded from the circle in Figure 11-3).

Whilst one of the sub-model clusters represented carbon emissions with respect to bus transportation, the other represented carbon emissions respectively for coach transportation. Further inquiry as a result of the extraction led to the discovery that both sub-models were wrongly connected by the data variable of 'carbon emissions for diesel buses per passenger-kilometre'. In the instance where this might have been intentional, this would have been due to a project specific assumption, for example, where coaches and buses might actually have similar emissions, and may indeed have been a carry-over from a previous project. Since the difference in emissions between these transportation modes is significant in the context of the eco-city case study, it meant the IRM model would have produced a calculation error. However, this has been corrected for later versions of the model as a direct result of interactive exploration of the extraction.

total variable count	total independent variable count	total / direct reference count	total independent reference count	total indirect reference count
2,357	1,117	3,404	1,516	41,068,458

Table 11.1: Total, Independent, and Indirect Variable and Reference Counts.

Extraction of the Metrics and Matrices of Complexity and Interdisciplinary Influences

From the extraction of the interconnected network of variables, or rather, the calculation graph produced as a result of model slicing for an optimisation objective/KPII, interdisciplinary influences have been automatically calculated. As a result, the metrics relevant to the variable count and distribution (VCD), the independent variable count and distribution (iVCD), and the reference count and distribution (RCD) were extracted. They were also in addition to the matrices for direct references (DR), indirect references (iDR), and indirect references (iDR). Table 11.1 shows the counts relevant to these metrics and matrices of total carbon emissions for the case study.

For the eco-city case study and total carbon emissions extraction, the metrics provided insight into the data requirements of each discipline or resource stream, and how input-model and output-model pairings were indeed connected, and the extent thereof. In some cases, it emerged that input-models were actually reliant upon data from other input-model or output-models and their pairings. Also with respect to total carbon emissions, the extracted matrices revealed how the multiple disciplines involved were indeed 'coupled'. It showed that energy and passenger-transport were most interconnected, but that the passenger-transport model was almost standalone from the other sub-models. In this instance, upon further inquiry, it emerged that much of the passenger-transport model was in fact external to the IRM model.

To further highlight the interconnectivity and interrelationships contributing to complexity, the valency of variables and the individual sub-model instability with respect to the overall IRM model's portability, were both calculated. They are described as follows.

- **Valency** - The number of cells each cell makes a reference to, and is referenced by to represent complexity and interconnectivity.
- **Instability** - A measure of a model's responsibility to, and independence from other models to identify where difficulty in adaptation might occur.

With respect to valency, a calculated average value of 2.89 in the context of total carbon emissions, provided a baseline marker to assess interconnectivity with respect to different disciplines, of which output-models demonstrated higher valencies. It was also revealed that a sub-model related to water was in fact more significantly interconnected than first thought and was a point for further inquiry. Table 11.2 (p.118) gives an example showing results of valency calculations from an IRM model.

Discipline Model	Cell Counts	Inputs	% Inputs	Average Valency
Land Use (LU)	38	24	63%	3.24
Socio Economic (SE)	38	23	61%	1.87
Passenger Trans (PT)	210	180	86%	1.57
Pass Trans Coeff (PTCo)	140	99	71%	2.44
Energy Demands (ED)	477	371	78%	1.89
Logistics (Lo)	133	111	83%	1.33
Logistics Coeff (LoCo)	16	16	100%	2.75
Water (Wa)	111	111	100%	1.00
Energy Supply (ES)	34	33	97%	1.79
Energy Sup Coeff (ESCo)	12	12	100%	6.00
Convert Factors (CF)	2	2	100%	18.00
Out: Energy Dem (SSED)	185	12	6%	3.32
Out: Energy Sup (SSES)	244	48	20%	4.40
Out: Logistics (SSLo)	67	0	0%	3.99
Out: Pass Trans (SSPT)	366	0	0%	3.71
Out: Socio-Econ (SSSE)	14	0	0%	4.21
Out: Water (SSW)	264	75	28%	4.08
Project Outputs (Out)	6	0	0%	14.83

Table 11.2: Example of Valency Results (Birch et al., 2013).

	Afferent Coupling (Responsibility)	Efferent Coupling (Independence)	Instability
Land Use	4	0	0%
Socio Economic	2	1	33%
Passenger Trans	1	0	0%
Pass Trans Coeff	1	0	0%
Energy Demands	1	0	0%
Logistics	1	0	0%
Logistics Coeff	1	0	0%
Water	1	0	0%
Energy Supply	1	0	0%
Energy Sup Coeff	1	0	0%
Convert Factors	2	0	0%
Out: Energy Dem	2	6	75%
Out: Energy Sup	2	3	60%
Out: Logistics	1	3	75%
Out: Pass Trans	2	2	50%
Out: Socio-Econ	2	2	50%
Out: Water	1	5	83%
Project Outputs	0	4	100%

Table 11.3: Example of Instability Results (Birch et al., 2013).

With respect to instability, input-models were more highly independent and less likely to be affected by adaptation with respect to changes in other interconnected sub-models. In contrast, the output-models that are invariably interconnected were indeed demonstrated with higher measures of instability, and therefore would be more impacted by changes within the overall IRM model. Furthermore, instability is also a small indication of where effects in changes of input will likely occur. However, in this instance sensitivity analysis would be more informative. Table 11.3 (p.119) gives an example of instability calculations also from the IRM model.

11.2.3 Applying Extraction and Analysis Methodology, and the Sensitivity Analysis of the Analysis Activity Phase

In support of the extracted interconnected network, relevant metrics and matrices, and as part of the activity phase 'analysis', a sensitivity analysis was applied to support the next steps of optimisation and also, in general exploration of the IRM model.

Preparations of Sensitivity Analysis and Insights Generated

With respect to the extraction of the IRM model relevant to total carbon emissions of the eco-city case study, relevant independent variables from the extraction phases were identified, and a test value was directly taken from the IRM model and the data it already contained. Discounting redundant variables such as conversion factors which did not impact a change with respect to decisions that might have been made, and of the 933 relevant variables, a confidence interval was assigned to bound each of these. The sensitivity analysis was then run and completed with over two thousand simulations, the results of which required normalising before assessment. In additon, further analyses of KPIs relevant to the same variables of the total carbon emissions as the KPII were also conducted.

	Normalised Sensitivity for CO_2e Emissions Per Capita		
Variable	**Total**	**Non-Domestic Buildings**	**External Transport**
FuelType Petrol City Car	100	0	100
CO2 emissions from gas combustion	91	100	0
FuelType Electric Heavy Rail	78	0	78
District Heat Demand - Gas Boiler	71	73	0
District Heat Efficiency - Gas Boiler	71	73	0
Gas Network Efficiency	68	83	0
Gas Network Demand	62	78	0
Electricity Demand from CHP	57	68	0
CH4 emissions from biomass	47	52	0
Efficiency of Heat from biomass	46	55	0

Table 11.4: Example of Sensitivity Analysis Results (Birch et al., 2013).

As a result of applying the sensitivity analysis, variable dominance was observed for the variables to which the KPII, or even KPI, were most sensitive to changes in. It provided an insight into the importance of each sub-model and the scope for affecting each with respect to the total carbon emissions. Specifically for the eco-city case study, the analysis also revealed the spread of fuel types, for example, natural gas more significantly affected carbon emissions of buildings over petrol used in passenger-transport, and inversely so. In another instance, when exploring the sensitivity analysis and masterplan-design, it was observed that district heating or combined heat and power (CHP) systems would have a suprising effect on the KPII if it were to be included. Table 11.4 gives an example showing the results of sensitivity analysis of an IRM model.

11.2.4 Applying Extraction and Analysis Methodology, and the Implications Towards the Optimise Activity Phase

As part of the complete actions that form the extraction and analysis within the methodology, EAM provided routes for designing and decision options, but also for investigation of the IRM model and its structure. In this way, EAM has helped the developers and the practioners of IRM modelling to better understand the design variables involved, the parameters, and the relationships that bound to specific optimisation objectives.

11.3 Chapter Conclusions

This chapter has demonstrated the application of extraction and analysis methodology (EAM) with real life examples and a case study of an industry-based multidisciplinary model that has been built as an interdisciplinary integrating platform. Together with the previous chapter, it has successfully demonstrated the approach of constrained optimisation for better exposing and handling complexity within the setting of complex interdisciplinary design in the context of the built environment that is especially affected by the influence of sustainability. In particular, the methodology allows the extraction of information relating to valency, instability, and sensitivity. In doing so, it has been shown that EAM supports the use of constraint-based thinking towards designing that is interdisciplinary and complex, and towards demonstrating constraint-based thinking does indeed enhance such designing.

Chapter 12

Conclusions: Constraint-based Thinking Towards Enhancing Complex Interdisciplinary Designing

"The more constraints one imposes, the more one frees one's self. And the arbitrariness of the constraint serves only to obtain precision of execution" - Igor Stravinsky

12.1 The Motivation of the Research and Achieving the Research Objectives

The motivation of this thesis has been to explore the inherent and increasingly interdisciplinary nature of designing and the complexities experienced by its various practitioners. It has aimed to answer the following research question.

"Can constraint-based thinking be applied to enhance existing practice of designing and efforts of design thinking in order to support that which is both interdisciplinary and complex?"

As a result, the thesis has presented a body of research work that has taken a wide perspective, and has brought together the current state-of-the-art in designing, constraints and constraint-based thinking, sustainability and sustainable development, and masterplanning within the design-based field of the built environment.

The thesis has demonstrated how constraint-based thinking can indeed be applied towards enhancing designing and design-based thinking through the research objectives, the achievements of which are described in the following, and concluding sections of this thesis.

12.1.1 To Critically Compare and Contrast Designing Processes and Their Significant Elements to Identify Common Features Towards a Simpler Perspective in Designing and Design-based Thinking

This thesis has critically compared and contrasted different designing process models. It has applied a problem solving perspective and observed that designing can be simply described as problem solving in all instances. They can also be identified by the significant elements of design-problem solving: establish, plan, understand, generate, evaluate, decide, and communicate. Furthermore, understanding is especially prominent towards design-problem solving to which designing, creativity, and cognition are all inextricably linked, and knowledge being the underlying connection and facilitator. The simplicity of these conclusions are considered valuable towards emerging challenges of complex interdisciplinary designing (Chapter 2).

12.1.2 To Explore the Use of Constraints and Constraint-based Thinking, their Associated Approaches, Tools, and Methods, Towards Enhancing Designing Process

This thesis has explored the nature of constraints as the foundation to constraint-based thinking and has considered what constraints are, where they arise from, and how different types of constraints are handled. It has applied constraint-based thinking as an approach towards designing whilst also maintaining a problem solving perspective. As such, this thesis has identified the inextricable link of constraints to creativity, designing, and cognitive process. It has also been demonstrated that constraints are prominent to knowledge discovery, knowledge handling, and are also rather significantly, a means of facilitating crucial understanding in design-problem solving. Constraints and constraint-based thinking has therefore been acknowledged in this thesis as having the potential to significantly contribute to designing of all kinds (Chapter 3).

12.1.3 To Explore Sustainable Development as an Example of Interdisciplinary Design and Therefore the Consequent Influence of Sustainability Upon So-called Sustainable Design

This thesis has explored sustainable development, sustainability, and the distinction between these as respectively being the process and the motivation as objectives for what is ideally achieved. It has also identified a newer perspective in which sutainable development and/or sustainability is described by the four, and not three, integrated elements of: people, planet, profit, and policy. Rather poignantly, this thesis has also observed the inherently interdisciplinary nature of sustainable development and the influences of sustainability that have caused a shift towards interdisciplinary designing, in general, and to which issues of complexity arise as a result of (Chapter 4).

12.1.4 To Explore the Built Environment as a Design-based Field That is an Example Inherently Interdisciplinary, Affected by Sustainability, and Demonstrates Complexity

In this thesis, the built environment was demonstrated as a design-based field that is driven by many influences including, but not limited to, legislation and statutory requirements and the impact of sustainability's integrated influences of people, planet, profit, and policy. The built environment has indeed been demonstrated as being inherently interdisciplinary, and the arising complexities of which are identified in this thesis within the contexts of people, practice, and precedence. The impacts thereof, were further explored in the specific example of masterplanning that was additionally investigated (Chapter 5).

12.1.5 To Propose Constraint-based Thinking as a Means of Enhancing Complex Interdisciplinary Designing

Constraint-based thinking as a methodology has been proposed in this thesis and it has been shown how such a methodology can be applied (Chapter 6).

12.1.6 To Demonstrate Constraint-based Thinking Enhances Existing Designing, and Towards That Which is Both Interdisciplinary and Complex

This thesis demonstrated constraint-based thinking enhances complex and interdisciplinary designing with a series of case studies that were each undertaken in order to do so.

A Complex and Interdisciplinary Instance of Design-based Practice to Which Constraint-based Thinking Can Be Applied

This thesis has demonstrated constraint-based thinking and its capabilities towards complex interdisciplinary designing by using the case study of integrated resource management (IRM) that inherently demonstrated the qualities of interdisciplinarity and complexity and was used as the setting for its investigations. It was shown that IRM can be regarded as a constraint system and forms a foundation for applying constraint-based thinking. It can handle interdisciplinary and complex designing associated with sustainability and the built environment. Constraints can exist between the variables in a single discipline, and between variables across disciplines (Chapter 7).

Even the Most Stringent Constraints in the Form of Legislation and Statutory Requirements Can Be a Positive Stimulus in Designing

This thesis applied constraint-based thinking with respect to case studies of product-related and process-related legislation and statutory requirements. They were respectively related to the environment and eco-design, and sustainability and sustainable development/design.

It was shown that the legislation and statutory requirements can be considered equivalent to constraints. They proved not to be a hindrance to design, but in fact stimulated innovative approaches. It was seen that constraints arise from sustainability considerations and these can be treated as an additional discipline in a constraint-based manner. In particular, these tend to form hard constraints which means that they must be integrated and tackled early on in the designing process (Chapter 8).

How Constraint-based Thinking Can Be Applied as an Instance of Interdisciplinary and Complex Designing and Thus How Design Can Be Translated Into a Constraint-based Methodology

This thesis applied constraint-based thinking and considered the impact of imposed design objectives and their respective key performance indicators (KPIs) as measures of achieving these. They were identified as being central to sustainable design and sustainability appraisal. However, it was demonstrated that they imposed upon what is possible, in the same way that constraints generally impose. The implications of imposed objectives, as KPIs and then as constraints, supported the idea that constraint-based thinking is an ideal approach. In particular, it was seen that the IRM environment is a suitable forum for constraint-based thinking and for holding the KPIs (Chapter 9).

An Approach Towards Interdisciplinary and Complex Designing Using Constraint-based Thinking

This thesis has used the instances of integrated resource management (IRM) in masterplanning and urban design of the built environment as examples of complex interdisciplinary design. It has been shown that constraint-based thinking can be applied to these successfully. It has been demonstrated that IRM is in fact a matter of constraints, and can be interpreted as an example of constrained optimisation. The extraction and analysis methodology (EAM) was created, based on defined optimisation objectives that constrained, but also facilitated understanding of the interconnections and interrelationships that occured. In particular, information on these interconnections can be extracted, including variable count or references, and their sensitivity. It was also seen that this exposed and handled complexity and proved effectively insightful towards focused design optimisation. This was successfully demonstated with a case study that reported how EAM had been applied in the context of an industry-based interdisciplinary modelling environment. (Chapter 10 and Chapter 11).

12.2 Future Work

Constraint-based thinking is not in itself a complex concept to prescribe to, but the perception of, and the true adoption in which such thinking would be applied, is where the effort of future work predominantly lies. The thesis has approached the research with a wide perspective, however, it has still demonstrated that design-based activities are inherently a matter of constraints. Efforts towards a different mindset in design-based thinking would progress incrementally, but would be achievable.

References

Al-Mashari, M., Al-Mudimigh, A., & Zairi, M. (2003). Enterprise resource planning: A taxonomy of critical factors. *European Journal of Operational Research*, 146(2), 352–364.

Alwaer, H. & Clements-Croome, D. (2010). Key performance indicators (kpis) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Building and Environment*, 45(4), 799–807.

Andreasen, M. & Hein, L. (1987). *Integrated Product Development*. IFS Publications.

Aronson, J. (2011). Sustainability science demands that we define our terms across diverse disciplines. *Landscape Ecology*, 26(4), 457–460.

Ayaz, E. & Levitas, J. (2008). Spatially linked integrated resource management (irm): A tool to inform eco-city planning. *Ecocity World Summit 2008*.

Baggott, S., Brown, L., Milne, R., Murrells, T., Passant, N., Thistlewaite, G., & Watterson, J. (2005). Uk greenhouse gas inventory, 1990 to 2003: Annual report for submission under the framework convention on climate change.

Barbier, E. (1987). The concept of sustainable economic development. *Environmental Conservation*, 14(02), 101–110.

Bartuska, T. (2007). *The Built Environment: Definition and Scope*, chapter 1, (pp. 3–14). John Wiley and Sons.

Basadur, M. (2004). Leading others to think innovatively together: Creative leadership. *The Leadership Quarterly*, 15(1), 103–121.

Baykan, C. & Fox, M. (1987). An investigation of opportunistic constraint satisfaction in space planning.

Bhowmick, S., Hovland, P., Norris, B., Strout, M., & Utke, J. (2005). Sensitivity analysis and design optimization through automatic differentiation. *Journal of Physics: Conference Series*, 16(1), 466.

Birch, D., Liang, H., Kelly, P., Mullineux, G., Field, T., Ko, J., & Simondetti, A. (2013). Multidisciplinary engineering models: Methodology and case study in spreadsheet analytics. *Proceedings of the European Spreadsheet Risks Interest Group (EuSpRIG) 2013*.

Blayney, P. (2006). An investigation of the incidence and effect of spreadsheet errors caused by the hard coding of input data values into formulas.

Blessing, L. & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. Springer Publishing Company, Incorporated, first edition.

Blumrich, J. (1970). Design. *Science*, 168(3939), 1551–1554.

Borremans, E. (2003). Climate change and power generation. *Institutional Investors Group on Climate Change*.

Bowen, J. (1997). Using dependency records to generate design coordination advice in a constraint-based approach to concurrent engineering. *Computers in Industry*, 33(23), 191–199.

Bowen, J., O'Grady, P., & Smith, L. (1990). A constraint programming language for life-cycle engineering. *Artificial Intelligence in Engineering*, 5(4), 206–220.

Braha, D. & Reich, Y. (2003). Topological structures for modeling engineering design processes. *Research in Engineering Design*, 14(4), 185–199.

Buscemi, M. & Montanari, U. (2008). A survey of constraint-based programming paradigms. *Computer Science Review*, 2(3), 137–141.

Carlowitz, H. v. (1713). *Silvicultura Oeconomica*. Carlowitz.

Chakraborty, B., Collins, L., Strecher, V., & Murphy, S. (2009). Developing multicomponent interventions using fractional factorial designs. *Statistics in Medicine*, 28(21), 2687–2708.

Chandrasekaran, B. (1990). Design problem solving: A task analysis. *AI Magazine*, 11(4), 59–71.

Chiang, T. & Trappey, A. (2007). Development of value chain collaborative model for product lifecycle management and its lcd industry adoption. *International Journal of Production Economics*, 109(1-2), 90–104.

Choi, J., Nies, L., & Ramani, K. (2008). A framework for the integration of environmental and business aspects toward sustainable product development. *Journal of Engineering Design*, 19(5), 431–446.

Chung, P. & Goodwin, R. (1998). An integrated approach to representing and accessing design rationale. *Engineering Applications of Artificial Intelligence*, 11(1), 149–159.

Clermont, M. (2005). Heuristics for the automatic identification of irregularities for spreadsheets.

Clevenger, C. & Haymaker, J. (2009). Framework and metrics for assessing the guidance of design processes.

Coello, C. (1999). A comprehensive survey of evolutionary-based multiobjective optimization techniques. *Knowledge and Information Systems*, 1(3), 129–156.

Coughlan, T. & Johnson, P. (2007). Constrain yourselves: exploring end user development in support for musical creativity.

Cox, G. (2005). Cox review of creativity in business: Building on the uk's strengths. *Design Council*.

Cross, N. (1989). *Engineering Design Methods*. John Wiley and Sons, first edition.

Cross, N. (2000). *Engineering Design Methods: Strategies for Product Design*. John Wiley and Sons, third edition.

Davenport, T. & Prusak, L. (2000). *Working Knowledge: How Organizations Manage What They Know*. Harvard Business School Press, second edition.

de Mast, J. (2011). The tactical use of constraints and structure in diagnostic problem solving. *Omega*, 39(6), 702–709.

De Meester, B., Dewulf, J., Verbeke, S., Janssens, A., & Van Langenhove, H. (2009). Exergetic life-cycle assessment (elca) for resource consumption evaluation in the built environment. *Building and Environment*, 44(1), 11–17.

Decout, S., Manel, S., Miaud, C., & Luque, S. (2012). Integrative approach for landscape-based graph connectivity analysis: a case study with the common frog (rana temporaria) in human-dominated landscapes. *Landscape Ecology*, 27(2), 267–279.

Deng, Y., Britton, G., & Tor, S. (2000). Constraint-based functional design verification for conceptual design. *Computer-Aided Design*, 32(14), 889–899.

Der-Petrossian, B. & Johansson, E. (2000). Construction and environment - improving energy efficiency. *Building Issues*, 10(2).

Design Council, U. (2005). Double diamond design process model.

Dieter, G. (1991). *Engineering Design: A Materials and Process Approach*. McGraw-Hill.

Eaton, R., Hammond, G., & Laurie, J. (2007). Footprints on the landscape: An environmental appraisal of urban and rural living in the developed world. *Landscape and Urban Planning*, 83(1), 13–28.

EC (2003a). Directive 202/95/ec of the european parliament and of the council of 27 january 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. *Official Journal of the European Union*, 46(19-23).

EC (2003b). Directive 202/96/ec of the european parliament and of the council of 27 january 2003 on waste electrical and electronic equipment (weee). *Official Journal of the European Union*, 46, 24–38.

EC (2005). Directive 2005/32/ec of the european parliament and of the council of 6 july 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending council directice 92/42/ec and diretices 96/57/ec and 2000/55/ec of the european parliament and of the council. *Official Journal of the European Union*, 48, 29–58.

Elkington, J. (2004). *Enter the Triple Bottom Line*, chapter 1, (pp. 1–16). Earthscan. Henriques, A. & Richardson, J.

Eppinger, S. (2011). The fundamental challenge of product design. *Journal of Product Innovation Management*, 28(3), 399–400.

Ervin, S. & Gross, M. (1987). Roadlab a constraint based laboratory for road design. *Artificial Intelligence in Engineering*, 2(4), 224–234.

Farsari, Y. & Prastacos, P. (2002). Sustainable development indicators: An overview. *International Conference of Citizens, Sustainable Development, Environment.*

Fiksel, J. (2012). *Design for Environment: A Guide to Sustainable Product Development.* McGraw-Hill, second edition.

Flager, F., Adya, A., & Haymaker, J. (2009). Aec multidisciplinary design optimization: Impact of high performance computing.

Flager, F. & Haymaker, J. (2009). *A Comparison of Multidisciplinary Design, Analysis and Optimization: Processes in the Building Construction and Aerospace.* Technical report, Center for Integrated Facility Engineering.

Frank, A. & Wallace, M. (1995). Constraint based modeling in a gis: Road design as a case study.

French, M. (1999). *Conceptual Design for Engineers.* Springer-Verlag, third edition.

Fuh, J. & Li, W. (2005). Advances in collaborative cad: the-state-of-the art. *Computer-Aided Design*, 37(5), 571–581.

Garner, S. & Mann, P. (2003). Interdisciplinarity: perceptions of the value of computer-supported collaborative work in design for the built environment. *Automation in Construction*, 12(5), 495–499.

GFN (2012). *Trends in Ecological Footprint and Biocapicity: UK Factsheet.* Technical report, Global Footprint Network.

Goel, T., Vaidyanathan, R., Haftka, R., Shyy, W., Queipo, N., & Tucker, K. (2007). Response surface approximation of pareto optimal front in multi-objective optimization. *Computer Methods in Applied Mechanics and Engineering*, 196(4-6), 879–893.

Goel, V. (1995). *Sketches of Thought.* MIT Press. Paper with Bo Eisen.

Goel, V. & Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science*, 16(3), 395–429.

Gross, M. (1985). *Design as Exploring Constraints.* PhD thesis. Massachusetts Institute of Technology (MIT).

Hammond, G. (2000). Energy, environment and sustainable development: A uk perspective. *Process Safety and Environmental Protection*, 78(4), 304–323.

Hammond, G. (2004). Science, sustainability and the establishment in a technological age. *Interdisciplinary Science Reviews*, 29(2), 193–208.

Hammond, G. (2006). people, planet and prosperity: The determinants of humanity's environmental footprint. *Natural Resources Forum*, 30(1), 27–36.

Handy, S., Boarnet, M., Ewing, R., & Killingsworth, R. (2002). How the built environment affects physical activity: Views from urban planning. *American Journal of Preventive Medicine*, 23(2, Supplement 1), 64–73.

Harridge, C., Mactavish, A., McAllister, I., & Nicholson, S. (2002). Guide to sustainability appraisal.

Hatchuel, A. & Weil, B. (2009). C-k design theory: an advanced formulation. *Research in Engineering Design*, 19(4), 181–192.

Hazelrigg, G. (1998). A framework for decision-based engineering design. *Journal of Mechanical Design*, 120(4), 653–658.

Hicks, B., Medland, A., & Mullineux, G. (2006). The representation and handling of constraints for the design, analysis, and optimization of high speed machinery. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)*, 20(4), 313–328.

Hicks, B. J., Medland, A., & Mullineux, G. (2003). A constraint-based approach for the optimum redesign of a packaging operation. *Packaging Technology and Science*, 16(4), 135–148.

HMSO (2008). Climate change act 2008 (chapter 27). *Her Majesty's Stationery Office*.

Hoekstra, A. (2009). Human appropriation of natural capital: A comparison of ecological footprint and water footprint analysis. *Ecological Economics*, 68(7), 1963–1974.

Hoffmann, C. (2005). Constraint-based computer-aided design. *Journal of Computing and Information Science in Engineering*, 5(3), 182–187.

Hoffmann, C., Sitharam, M., & Yuan, B. (2004). Making constraint solvers more usable: overconstraint problem. *Computer-Aided Design*, 36(4), 377–399.

Howard, T., Culley, S., & Dekoninck, E. (2008). Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies*, 29(2), 160–180.

Hulme, K. & Bloebaum, C. (2000). A simulation-based comparison of multidisciplinary design optimization solution strategies using cascade. *Structural and Multidisciplinary Optimization*, 19(1), 17–35.

IGT (2010). Low carbon construction igt: Final report.

İlal, M. (2007). The quest for integrated design system: A brief survey of past and current efforts. *Middle East Technical University Journal of the Faculty of Architecture*, 24(2), 149–158.

Jakeman, A. & Letcher, R. (2003). Integrated assessment and modelling: Features, principles and examples for catchment management. *Environmental Modelling and Software*, 18(6), 491–501.

Johansson, G. (2002). Success factors for integration of ecodesign in product development: A review of state of the art. *Environmental Management and Health*, 13, 98–107.

Jonassen, D. (1997). Instructional design models for well-structured and iii-structured problem-solving learning outcomes. *Educational Technology Research and Development*, 45(1), 65–94.

Jones, T. (1983). An integrating framework for research in business and society: A step toward the elusive paradigm? *The Academy of Management Review*, 8(4), 559–564.

Jörby, S. (2002). Local agenda 21 in four swedish municipalities: A tool towards sustainability? *Journal of Environmental Planning and Management*, 45(2), 219–244.

Kain, J. (2000). *Urban Support Systems*. PhD thesis. Department of Built Environment and Sustainable Development Architecture, Chalmers University of Technology, Göteborg, Sweden.

Kang, E., Jackson, E., & Schulte, W. (2011). An approach for effective design space exploration.

Keiner, M. (2005a). History, definition(s) and models of "sustainable development". Spatial and Urban Planning, Landscape Architecture.

Keiner, M. (2005b). Re-emphasizing sustainable development the concept of evolutionability. *Environment, Development and Sustainability*, 6(4), 379–392.

Kepran, H. (2002). *Heidelberg. Creating a Framework for Integrated Resource Management*. Technical report, International Council for Local Environmental Initiatives (ICLEI).

Klosterman, R. (2011). Planning theory education: A thirty-year review. *Journal of Planning Education and Research*, 31(3), 319–331.

Kohler, N. & Moffatt, S. (2003). Life-cycle analysis of the built environment. *UNEP Industry and Environment: Sustainable Building and Construction*, 26(2-3), 17–21.

Kueng, P. (2000). Process performance measurement system: A tool to support process-based organizations. *Total Quality Management*, 11(1), 67–85.

Kuhn, T. (1961). The function of measurement in modern physical science. *Isis*, 52(2), 161–193.

Kuhn, T. (1970, 1962). *The Structure of Scientific Revolutions*. The University of Chicago Press, second, enlarged edition.

Lai, Y. (2009). A constraint-based system for product design and manufacturing. *Robotics and Computer-Integrated Manufacturing*, 25(1), 246–258.

Lauder, J. (2012). *Sustainability: New Perspectives and Opportunities*, volume Globalization TrendLab 2012. Trustees of the University of Pennysylvania.

Lawson, B. (2005). *How Designers Think: The Design Process Demystified*. Architectural Press, fourth edition.

Lee, H., Lee, R., & Yu, G. (1996). Constraint logic programming for qualitative and quantitative constraint satisfaction problems. *Decision Support Systems*, 16(1), 67–83.

Liang, H. & Birch, D. (2011). Extraction and analysis methodology for supporting complex sustainable design. *International Conference on Engineering Design, ICED'11, Copenhagen, Denmark.*

Liang, H., Mullineux, G., & Hammond, G. (2008). A constraint-based approach to sustainable design and development. NordDesign 2008, Tallinn, Estonia.

Lubart, T. (2001). Models of the creative process: Past, present and future. *Creativity Research Journal*, 13(3-4), 295–308.

Mackworth, A. & Freuder, E. (1993). The complexity of constraint satisfaction revisited. *Artificial Intelligence*, 59(12), 57–62.

Martínez, M. & Félez, J. (2005). A constraint solver to define correctly dimensioned and overdimensioned parts. *Computer-Aided Design*, 37(13), 1353–1369.

Matthews, J. (2007). *A Constraint-based Approach for Assessing the Capabilities of Existing Designs to Handle Product Variation.* PhD thesis. Department of Mechanical Engineering. Chapter 3.

Mayer, M. (2006). Creativity loves constraints. Bloomberg Businessweek.

McAlpine, H. (2010). *Improving the Management of Informal Engineering Information through Electronic Logbooks.* PhD thesis. Department of Mechanical Engineering.

McMahon, C. (2011). *The Future of Design Research: Consolidation, Collabration and Inter-Disciplinary Learning?* The Future of Design Methodology. Springer. editor - Birkhofer, H.

McMahon, C. & Draper, C. (2002). Patterns of design and development in adaptive design: How do we match design method to design circumstance?

Medland, A. & Matthews, J. (2011). The implementation of a direct search approach for the resolution of complex and changing rule-based problems. *Engineering with Computers*, 27(2), 105–115.

Medland, A. & Mullineux, G. (1988). *Principles of CAD: A Coursebook.* Kogan Page, Limited.

Miguel, I. & Prestwich, S. (2007). *Constraint Modeling and Reformulation: Introduction*, (pp. 148–150). ISTE Ltd: London. Benhamou, F., Jussien, N. & O'Sullivan, B.

Mitchard, N., Frost, L., Harris, J., Baldrey, S., & Ko, J. (2011). Assesing the impact of road schemes on people and communities. *Proceedings of the Institute of Civil Engineers*, Engineering Sustainability 164(3), 185–196.

Mongomery, D. (2004). *Design and Analysis of Experiments.* John Wiley & Sons. Inc., sixth edition.

Mostow, J. (1985). Toward better models of the design process. *AI Magazine*, 6(1), 44–57.

Mullineux, G. (2001). Constraint resolution using optimisation techniques. *Computers and Graphics*, 25(3), 483–492.

Mullineux, G., Hicks, B., & Medland, T. (2005). Constraint-aided product design. *Acta Polytechnica*, 45(3), 31–36.

Murray, S. (2007). *Action or Aspiration? Sustainability in the British workplace.* Technical report, The Economist Intelligence Unit.

Niku, S. (2009). *Creative Design of Products and Systems.* John Wiley and Sons.

Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization Science*, 5(1), 14–37.

NPPF (2012). *National Planning Policy Framework.* Technical report, Department for Communities and Local Government.

OED (2012). *"Design".* Oxford University Press.

O'Hare, J., Dekoninck, E., Liang, H., & Turnbull, A. (2007). An empirical study of how innovation and the environment are considered in current engineering design practise. Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, 213–218.

Olundh, G. (2006). *Modernising Ecodesign: Ecodesign of Innovative Solutions.* PhD thesis. Royal Institute of Technology.

Onarheim, B. & Wiltschnig, S. (2010). Opening and constraining: constraints and their role in creative processes.

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on lca. *Construction and Building Materials*, 23(1), 28–39.

O'Sullivan, B. (2002). Interactive constraint-aided conceptual design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)*, 16(4), 303–328.

Page, J., Grange, N., & Kirkpatrick, N. (2008). The integrated resource management (irm) model: A guidance tool for sustainable urban design. 25th Conference on Passive and Low Energy Architecture, PLEA'08.

Pahl, G. & Beitz, W. (1984). *Engineering Design: A Systematic Approach.* Design Council and Springer Verlag, first edition.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. (2007). *Engineering Design: A Systematic Approach.* London: Springer-Verlag, third edition.

Panko, R. (1998). What we know about spreadsheet errors. *Journal of End User Computing*, 10(2), 15–21. Revised Edition.

Papalambros, P. & Wilde, D. (2000). *Principles of Optimal Design: Modeling and Computation.* Cambridge University Press, second edition.

Pascual, O. & Boks, C. (2004). An overview of environmental product performance meausrement in the asian electronics industry.

Plackett, R. & Burman, J. (1946). The design of optimum multifactorial experiments. *Biometrika*, 33(4), 305–325.

Polyani, N. (1966). *The Tacit Dimension*. London: Routledge.

POST (2006). Carbon footprint of electricity generation. *Parliamentary Office of Science and Technology*, (Postnote Number 268).

Preiss, K. (1980). Data frame model for the engineering design process. *Design Studies*, 1(4), 231–243.

Pugh, S. (1991). *Total Design. Methods for Successful Product Engineering*. Addison-Wesley, second edition.

Ralph, P. & Wand, Y. (2009). *A Proposal for a Formal Definition of the Design Concept*, volume 14 of *Lecture Notes in Business Information Processing*, (pp. 103–136). Springer Berlin Heidelberg.

Ravetz, J. (2000). Integrated assessment for sustainability appraisal in cities and regions. *Environmental Impact Assessment Review*, 20(1), 31–64.

Rees, W. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization*, 4(2), 121–130.

Régin, J.-C. (2004). *Global Constraints and Filtering Algorithms*, volume 27 of *Operations Research/Computer Science Interfaces Series*, chapter 4, (pp. 89–135). Springer US. Milano, Michela.

RIBA (2012). Riba plan of work 2013: Consultation document. Royal Institute of British Architects.

Roof, K. & Oleru, N. (2008). Public health: Seattle and king county's push for the built environment. *Journal of Environmental Health*, 71(1), 24–27.

Rudolph, S. & Blling, M. (2004). Constraint-based conceptual design and automated sensitivity analysis for airship concept studies. *Aerospace Science and Technology*, 8(4), 333–345.

Sahinidis, N. (2003). *Global Optimization and Constraint Satisfaction: The Branch-and-Reduce Approach*, volume 2861 of *Lecture Notes in Computer Science*, (pp. 1–16). Springer Berlin / Heidelberg.

Senescu, R., Mole, A., & Fresquez, A. (2006). A case study in structural drafting, analysis and design using an integrated intelligent model.

Shea, K., Aish, R., & Gourtovaia, M. (2005). Towards integrated performance-driven generative design tools. *Automation in Construction*, 14(2), 253–264.

Simon, H. (1996). *The Sciences of the Artificial*. MIT Press, third edition.

Singh, B., Matthews, J., Mullineux, G., & Medland, A. (2006). Embedding general constraint resolution into a cad system.

Singh, B., Matthews, J., Mullineux, G., & Medland, A. (2007). Exploring design space using multi-instance modelling.

Spangenberg, J. & Bonniot, O. (1998). Sustainability indicators: A compass on the road towards sustainability. *Wuppertal Institute for Climate, Environment and Energy*, Wuppertal Papers(81).

Stokes, P. (2007). Using constraints to generate and sustain novelty. *Psychology of Aesthetics, Creativity, and the Arts;Psychology of Aesthetics, Creativity, and the Arts*, 1(2), 107–113.

Stokes, P. (2009). Using constraints to create novelty: A case study. *Psychology of Aesthetics, Creativity, and the Arts;Psychology of Aesthetics, Creativity, and the Arts*, 3(3), 174–180.

Stokes, P. & Fisher, D. (2005). Selection, constraints, and creativity case studies: Max beckmann and philip guston. *Creativity Research Journal*, 17(2-3), 283–291.

Subrahmanian, E., Rachuri, S., Fenves, S., Foufou, S., & Sriram, R. (2005). Product lifecycle management support: A challenge in supporting product design and manufacturing in a networked economy. *International Journal of Product Lifecycle Management*, 1(1), 4–25.

Suh, N. (1990). *Oxford Series on Advanced Manufacturing. The Principles of Design.* Oxford University Press, Inc.

Tan, R. & Culaba, A. (2002). *Environmental Life-Cycle Assessment: A Tool for Public and Corporate Policy Development.*

Thierauf, R. (1999). *Knowledge Management Systems for Business.* Greenwood Press.

Ugwu, O. & Haupt, T. (2007). Key performance indicators and assessment methods for infrastructure sustainability a south african construction industry perspective. *Building and Environment*, 42(2), 665–680.

Ugwu, O., Kumaraswamy, M., Wong, A., & Ng, S. (2006a). Sustainability appraisal in infrastructure projects (susaip): Part 1. development of indicators and computational methods. *Automation in Construction*, 15(2), 239–251.

Ugwu, O., Kumaraswamy, M., Wong, A., & Ng, S. (2006b). Sustainability appraisal in infrastructure projects (susaip): Part 2: A case study in bridge design. *Automation in Construction*, 15(2), 229–238.

Ullman, D. (1997). *The Mechanical Design Process.* McGraw-Hill, second edition.

Ulrich, K. & Eppinger, S. (2012). *Produt Design and Development.* New York: McGraw-Hill, fifth edition.

Unger, D. & Eppinger, S. (2009). Comparing product development processes and managing risk. *International Journal of Product Development*, 8(4), 382–402.

Vachon, S. & Klassen, R. (2008). Environmental management and manufacturing performance: The role of collaboration in the supply chain. *International Journal of Production Economics*, 111(2), 299–315.

Van Hentenryck, P., Simonis, H., & Dincbas, M. (1992). Constraint satisfaction using constraint logic programming. *Artificial Intelligence*, 58(13), 113–159.

Veeramachaneni, K., Vladislavleva, K., & O'Reilly, U. (2010). Feature extraction from optimization data via datamodeler's ensemble symbolic regression.

Von Stoker, T. & Steinemann, M. (2004). Sustainable development in switzerland: Methodological foundations. *Swiss Agency for Development and Cooperation (SDC) and Federal Office for Spatial Development (ARE).*

Wackernagel, M. (1994). *Ecological Footprinting and Appropriated Carrying Capacity: A Tool for Planning Toward Sustainability.* PhD thesis. University of British Columbia.

Wallas, G. (1926). *The Art of Thought.* London: Jonathon Cape. "famous model of thought".

Walsh, G. (1975). *Methods of Optimization.* John Wiley & Sons Ltd.

Ward, I. (2008). What are the energy and power consumption patterns of different types of built environment? *Energy Policy*, 36(12), 4622–4629.

WCED (1987). *Our Common Future.* Switzerland: World Commission on Environment and Development.

Weidman, T. & Minx, J. (2007). *A Definition of 'Carbon Footprint'*, (pp. 1–11). Nova Science Publishers: New York. Pertsova, C.C.

Wilkinson, P., Smith, K., Beevers, S., Tonne, C., & Oreszczyn, T. (2007). Energy, energy efficiency, and the built environment. *The Lancet*, 370(9593), 1175–1187.

Woo, J.-H., Clayton, M., Johnson, R., Flores, B., & Ellis, C. (2004). Dynamic knowledge map: reusing experts' tacit knowledge in the aec industry. *Automation in Construction*, 13(2), 203–207.

Wynn, D. & Clarkson, J. (2005). *Models of designing: Design process improvement*, (pp. 34–59). Springer London.

Xie, H., Henderson, P., & Kernahan, M. (2005). Modelling and solving engineering product configuration problems by constraint satisfaction. *International Journal of Production Research*, 43(20), 4455–4469.

Yan, X. & Sawada, H. (2006). A framework for supporting multidisciplinary engineering design exploration and life-cycle design using underconstrained problem solving. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)*, 20(4), 329–350.

Younger, M., Morrow-Almeida, H., Vindigni, S., & Dannenberg, A. (2008). The built environment, climate change, and health: Opportunities for co-benefits. *American Journal of Preventive Medicine*, 35(5), 517–526.

Yue, H., Brown, M., He, F., Jia, J., & Kell, D. (2008). Sensitivity analysis and robust experimental design of a signal transduction pathway system. *International Journal of Chemical Kinetics*, 40(11), 730–741.

Zamanian, M. & Pittman, J. (1999). A software industry perspective on aec information models for distributed collaboration. *Automation in Construction*, 8(3), 237–248.

Appendix

Publications

The following papers have been published and are reproduced in this appendix.

O'Hare, J., Dekoninck, E., **Liang, H.**, & Turnball, A. (2007). An Empirical Study of How Innovation and the Environment are Considered in Current Engineering Design Practise. Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses. 14th CIRP Conference on Life Cycle Engineering 2007, Waseda University, Tokyo, Japan

Liang, H., Mullineux, G., & Hammond, G. (2008). A Constraint-based Approach to Sustainable Design and Development. NordDesign 2008, Tallinn, Estonia.

Liang, H., & Birch, D. (2011) Extraction and Analysis Methodology for Supporting Complex Sustainable Design. International Conference on Engineering Design, ICED'11, Copenhagen, Denmark.

Birch, D., **Liang, H**., Kelly, P., Mullineux, G., Field, T., Ko, J., & Simondetti, A. (2013) Multidisciplinary Engineering Models: Methodology and Case Study in Spreadsheet Analystics. European Spreadsheet Risks Interest Group (EuSpRIG) 2013, London.

An Empirical Study of how Innovation and the Environment are Considered in Current Engineering Design Practise

Jamie O'Hare[1], Elies Dekoninck[1], Helen Liang[1], Aidan Turnbull[2]

[1] Engineering Innovative Manufacturing Research Centre, University of Bath, Bath, UK

[2] ENVIRON UK Ltd., WEEE, RoHS & Eco-design Practice, Hartham Park, Corsham, UK

Abstract

This paper reports the findings of a study of the current innovation and environmental considerations of six businesses that design and manufacture products affected by the product-related environmental legislation. Activities undertaken with the businesses provide insights into their New Product Development (NPD) processes, their innovation capabilities and their actions to improve their environmental performance. Several features of their NPD processes are suggested as presenting opportunities for eco-design tools to be integrated into design practises without negatively affecting the current NPD process. Finally, a conceptual framework is proposed which highlights the inter-relations between business, environmental, and customer requirements of a product across its lifecycle.

Keywords: Eco-design; New Product Development; Design tools

1 INTRODUCTION

It has been widely noted that although a wide range of eco-design tools have been developed relatively few of them have been adopted into industrial practices [1]. One response from researchers has been to propose modified NPD models which emphasise the integration of eco-design tools into the process [2] [3]. However, it has been noted that in practice, of the relatively few businesses who have adapted their NPD process to improve product environmental performance, most have ignored the models proposed by academic researchers and have instead developed their own models based on real-life practice [4].

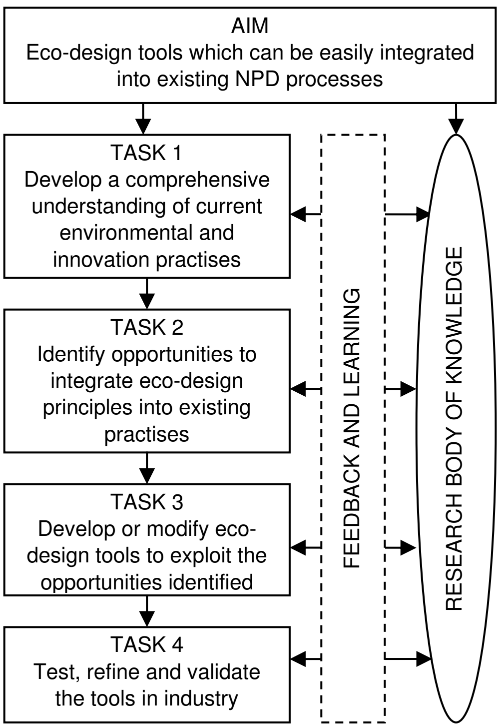

Figure 1: Research aims

This research takes the alternative approach in which the aim is to modify existing eco-design tools or develop new ones such that they fit into the existing NPD process of the business [5]. This paper reports on a study of the innovation and environmental practises of six businesses in the South-West of England. The results of this study along with the subsequent analysis contribute towards the completion of tasks 1 and 2 of the wider research program, as shown in Figure 1.

2 METHODOLOGY

2.1 Selection and recruitment of businesses

The study was conducted with six businesses that design and manufacture products in the South-West of England with product ranges that are likely to be affected by the Waste Electrical and Electronic Equipment (WEEE) [6], Restriction of

Business	Size	Product Range
A	Medium	Professional audio equipment
B	Medium-Large	Location/inspection equipment, sensors
C	Medium	Water/central heating controls, utilities metering
D	Medium	Heating, ventilation and hot water systems
E	Medium	Vending machines
F	Small	Industrial testing equipment

Table 1. Characteristics of the businesses surveyed

Hazardous Substances (RoHS) [7], or Energy Using Products (EuP) Directives [8]. Whilst primarily a study of design activities, there was interest in selecting businesses who also manufacture in the area as this would lead to greater engagement with the manufacturing process and so greater knowledge of the environmental impacts of the product.. The research literature has suggested that product-related environmental legislation is a strong driver for eco-design [9] and hence by selecting businesses affected by such legislation it was hoped that further insight could be gained into the validity of this idea. Business characteristics are summarised in Table 1

2.2 Development of research methods

The aim of the research was to gain an understanding of the **real** practises of businesses. It was therefore decided to develop a range of activities which would require the business to demonstrate their environmental and innovation performance and capabilities by providing evidence and concrete examples.

The visits lasted around three hours and the participants generally included, as a minimum, the Environmental, Manager (or equivalent) and the Design/Technical Manager. A typical visit programme is shown below with subsequent sections providing details of the key activities.

Visit programme

- Presentation by the researchers on the latest developments in the WEEE, RoHS and EuP Directives followed by discussions on how they affect the business
- Activity to assess the level of environmental 'pro-activity' of the business within its supply chain
- 'Life cycle Thinking' activity to assess current environmental actions throughout the product life cycle
- Factory tour
- New Product Development (NPD) process mapping activity
- Innovation benchmarking questions
- Recording of the business's current 'innovation funnel'

Life cycle thinking activity

A chart listing the seven lifecycle phases was presented to the participants who were given a brief explanation of the principles of life cycle thinking. The researcher then went through each lifecycle phase asking for examples of where actions or initiatives had been taken by the business to reduce the environmental impacts associated with that phase, prompting where necessary.

NPD process mapping

This activity was introduced by presenting the participants with examples of both formal and less formal NPD process models and asking which of the examples most closely related to the businesses' own processes. The participants were then asked to talk through and map out their own NPD process on a flipchart. This was map was further elaborated by asking the participants to add comments to identify general strengths, in green pen, and general weaknesses, in red pen.

Innovation benchmarking questions

An abridged version of the UK DTI's 'Living Innovation' [10] benchmarking questionnaire was used. Three sets of three questions covered the businesses' ability to 'Inspire' their designers, 'Connect' with their customers and suppliers, and successfully 'Create' – take good ideas into manufacture. Each question was written on a separate small card with a 4 point Likert-type scale at the bottom where one participant noted the consensus of the group by ticking the appropriate box. This consensus-seeking method was intended to obtain a response which was as representative of 'the business' as possible.

3 RESULTS

In order to facilitate inter-business comparison and benchmarking, a quantitative scoring system was developed for some of the activities. The scoring system for the activities and the business results are presented here:

Supply-chain pressures activity

Businesses who applied more environmental pressures on their suppliers than they received from their customers where deemed to be environmentally 'pro-active' in their supply chain, and vice-versa. Businesses were awarded 0 to 4 points for this activity depending on their level of 'pro-activity' with a score of 2 indicating a neutral balance. Only one business was considered to be 'pro-active' on environmental issues according to the criteria, half of the businesses were found to be 'reactive', and the remainder were 'neutral'.

Life cycle thinking activity

Table 2 shows the number of businesses who have made 'significant' efforts in each of the life cycle phases. A 'significant' effort point was awarded if a business was able to provide three or more examples of initiatives or methods they use to which would also reduce the environmental impacts during that particular phase. Two-thirds of the businesses were able to demonstrate significant effort in three of the lifecycle phases with the remaining businesses able to demonstrate significant effort in at least one phase.

Life cycle phase	Companies making a 'significant effort'
New concepts	2
Selection and use of materials	1
Production optimisation	5
Distribution system	3
Impacts during use	1
End-of-life strategy	3

Table 2: Results of life cycle thinking activity

Innovation benchmarking questions

The innovation benchmarking questions were scored by awarding +2 points for a 'strongly agree' response, +1 for an 'agree' response, and conversely -1 and -2 points were awarded for 'disagree' and 'strongly disagree' responses respectively. All businesses scored positively on the benchmarks but the scores varied considerably from +4 to +12 points. In all cases the scores appeared to be consistent with the researchers' views as to the relative innovation 'strength' of the businesses.

4 DISCUSSION

4.1 Environmental performance of businesses

Supply-chain pressures activity

Several of the companies commented that there had been an increase in the dialogue between the business and their supply-chain in recent years. In most cases this dialogue appeared to be limited to issues directly relating to compliance with legislation such as the WEEE and RoHS Directives. However in some cases customers were now requesting information on wider issues such as if the business had and environmental management system. Whilst most businesses had responded to requests for information from customers, it did not appear that they had made efforts to improve the environmental performance of their products beyond the minimum standards required for legislative compliance.

Life cycle thinking activity

From Table 2 it is noteworthy that five of the manufacturers have made significant efforts to reduce environmental impacts through 'production optimisation'. This is logical given that improvements made to the production phase are likely to lead direct cost-savings for the manufacturer i.e. through reduced energy costs or waste minimisation. The wide-spread interest in 'cleaner production' during the 1990s is another likely explanation of the success seen in this area.

In contrast, just one manufacturer had made significant improvements to the 'impacts during use' of their products. Businesses A, D and E manufacture products clearly have very significant impacts during their use phase and yet only one had made significant improvements in this area. The question therefore presents itself as to why the other two manufacturers had not yet attempted to make improvements in the use phase of their products' lifecycle? In both cases the businesses estimated the use phase as being the posing the greatest environmental burden, therefore lack of awareness is ruled out. In fact both businesses explained that energy efficiency was not an important consideration for their customers, which was reflected in their product specification and weightings.

Whilst undertaking the life cycle thinking activity with businesses it was noted that they were often unable to recognise the benefits that their 'cost-saving' activities where having on the environment (i.e. reducing material usage) without significant prompting from the researchers. It is suggested that this is because these activities had originally been framed as 'cost-saving' activities and the participants struggled to view these activities through an 'environmental frame'.

Several businesses commented that they were pleasantly surprised by the number of positive environmental actions that were attributed to the business within the life cycle thinking activity. Furthermore, four out of the five businesses who completed feedback forms following the visit agreed or strongly agreed that due to the visit they planned to improve their environmental actions. This implies that the activity had gone some way towards 'establishing a new mindset in which the importance of the environmental issues is established' – an important factor for the success of eco-design activities according to the literature [16].

4.2 Innovation capabilities of businesses

NPD process mapping

The NPD models were analysed with a view to identifying popular tools or methods; and similarities or features of the process which might provide suitable 'entry-points' for eco-design. The results of this analysis are presented in Table 3.

One weakness which was mentioned by the majority of the businesses concerned the difficulty in developing an accurate and stable requirements specification. Many businesses mentioned that work progressed even when the requirements specification had not been formally agreed or that changes to the specification were often made even after it had been agreed. This was perceived as wasting engineering effort and slowing project progress. Research literature suggests that the formulation of the requirements specification is a key stage for the integration of environmental considerations [17]. This suggests that there are opportunities for methods which can both improve the requirements specification formulation process and integrate environmental considerations.

Innovation funnel

It was observed that businesses found it difficult to discuss 'failed' projects and struggled to provide examples of failed projects. Academic literature [18] suggests that successful innovators have a high number of projects drop out of the NPD process but that these failures are mitigated by failing

Common 'Strengths'	Business benefit	Eco-design opportunity
Use of QFD	Ensure that requirements specification accurately represents needs of customer	Promote use of QFD for the Environment [11] which extends existing QFD tools by including the 'voice of the Environment' to set environmental targets
Regular safety and compliance reviews	Avoid the negative cost, time and brand image implications of producing non-compliant or unsafe products	Include an environmental review as part of the safety review – cover both environmental compliance and ensure environmental targets will be met [12]
Strong emphasis on cost-management and designing to a price point	Ensure that product is price competitive within its market segment	Use of financial methods such as environmental accounting [13], or Eco-Value [14] to emphasis cost benefits to business and customer of eco-design
Customer feedback as an input to the design process	Ensure that customer requirements are understood	Enhance customer focus by moving from 'eco-efficient' satisfaction of *requirements* to the effective fulfilment of *needs* through 'co-development' methods [15]

Table 3: Opportunities for eco-design within existing NPD process models

‘early’ i.e. before significant time and resources have been committed to the project. Several businesses commented that they made efforts to learn from their failed projects, but overall it was concluded that the ‘fail early and often’ culture was not present in any of the businesses studied.

A number of differences were noted between the innovation tunnels of the businesses in terms of the number of new projects launched per year, the time taken in development etc. However, no further generalisations can be drawn from these results as it is likely that the variations observed are as much due to contextual factors (such as the technology cycle of the industry, the size of the business, the legislative environment) as they are to the innovation strategy or culture of the business.

4.3 Development of a conceptual frame work

It was noted in section 4.1 that the businesses studied in this project struggled to recognise the environmental benefits often associated with their cost-driven actions. It was also noted that many of the businesses placed significant emphasis on trying to capture and understand the customer’s requirements within the NPD process as is reflected in the structure of their NPD processes and the common use of tools such as QFD. Based on these two observations it was suggested that a conceptual framework which clarifies the inter-relationships between the business, environmental, and customer requirements of a product would be useful. In the following section a conceptual framework which links the requirements of a product across its life cycle from the perspectives of the business, the environment and the customer is presented, its relevance to previous work is discussed, and finally applications of the framework are suggested.

Previous work linking the business, environmental, and customer aspects of product development

Although by no means a comprehensive review, there follows a summary of how the BEC Synergies diagram relates to similar frameworks presented in the research literature,.

In discussing the links between business, customers, and the environment a key theme which emerges from the literature is the problem of how to motivate a business to consider the environmental aspects of product development (it is assumed here that businesses are already motivated to meet customer product requirements). Given that businesses are essentially economically driven, one logical approach which has received much attention is to emphasise the link between environmental and economic performance. For example, the World Business Council for Sustainable Development make through what they term ‘eco-efficiency’. They state that eco-efficiency say is achieved, ‘…by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth’s estimated carrying capacity’ [19].

In adopting this philosophy, the logical question for a business to ask is ‘when does it pay to be green?’. Reviewers have commented that several attempts have been made to answer this question [20] with varying and sometimes conflicting responses. However, other authors have suggested that trying to prove or disprove this link has led to a polarising of the debate and that rather the question should instead be ‘when does it make sense to be green?’ [20]. What is clear is that there are a range of tools available which attempt to quantify the links between environmental and economic performance e.g. [13] .

Another major focus of research has been in understanding the stakeholders within the environmental NPD process, including their roles, and interactions. A stakeholder map has been proposed [21] which categorises stakeholders in terms of their ability to influence products characteristics. The model distinguishes three levels of stakeholder with the most

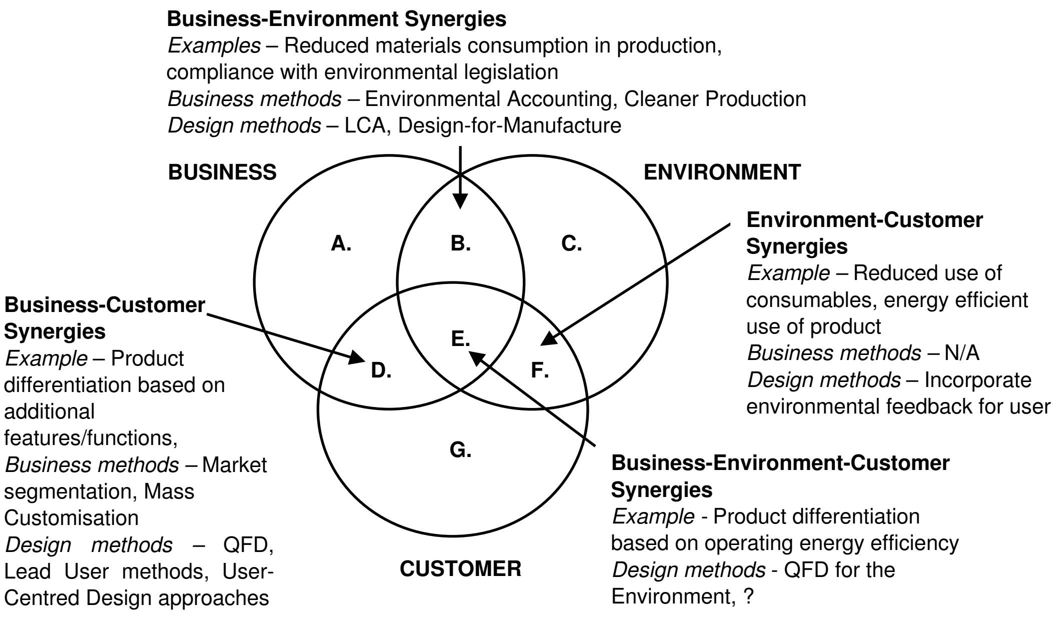

Figure 2: The inter-relations between business, environmental and customer requirements across the product life cycle

influential being the 'Design Team', followed by the 'Product Chain' and the 'External Stakeholders'. Other work [22] has extended the existing Customer Value Chain Analysis tool to include environmental considerations. The major stakeholders are listed and the links between these parties are drawn using a notation system to distinguish between the three types of flow: money, stuff (machines, materials, information etc), and issues (complaints, regulatory influences etc). This method allows the business to ascertain who the key project customers are, and by further analysing the flow of money, stuff and issues between these key parties, the 'Voice Of the Customer' (VOC) can be generated.

The final research focus has been on how to generate a list of product requirements to represent the views and interests of the key stakeholders. A work pack produced by the US Environmental Protection Agency [23] encourages the business to consider the product in terms of legal, cultural, cost, performance and environmental requirements. A separate matrix is populated with requirements for each of these areas, with the environmental matrix using axes of product lifecycle phase against 'product', 'process' and 'distribution'.

A somewhat similar tool which focuses on purely on environmental and functional requirements is QFD for the Environment (QFDE) [11]. QFDE can assist in formulating a requirements specification by incorporating both the 'Voice of the Customer' and the 'Voice of the Environment'. The requirements of the business are considered to some extent if we assume that meeting the customer's requirements is a major requirement and benefit for the business. QFDE is particularly useful in that it quantifies the conflicts between requirements and hence it can be used when making design decisions requiring a trade-off between competing requirements.

Unfortunately, none of the tools or methods discussed here can represent the product requirements from the viewpoint of the business, the environment and the customer **simultaneously**. Recognition of this fact led to the development of the 'Business-Environment-Customer Synergies' diagram presented in the following section.

The Business-Environment-Customer Synergies Diagram

The Business-Environment-Customer (BEC) Synergies diagram shown in Figure 2. is intended to classify, and represent the inter-relations between, the key stakeholder requirements of the product throughout its lifecycle (referred to from now on as simply 'product requirements'). Product requirements are positioned on the diagram according to the stakeholders which that particular requirement will benefit. Here, the term 'synergy' has been used to describe requirements which benefit more than one stakeholder. We can further define 'dual benefits' as a product requirement which benefits two stakeholders (i.e. sections B., D., or F.), and a 'tri-benefit' as a requirement which benefits all three stakeholders (i.e. section E.). Product differentiation based on additional product features or functions is an example of a dual-benefit as it: benefits the customer who receives a product which meets additional requirements beyond the primary functional requirements; and it benefits the business who can use those additional features to distinguish their product from the range of competing products which perform the same primary function.

Beyond this classification of product requirements, the BEC Synergies diagram can be used to classify the types of business methods or design tools which may be appropriate when attempting to fulfill the requirements within a sector. For example, the identification of market segments and the use of Quality Functional Deployment may be an appropriate business method and design tool respectively for fulfilling the product differentiation requirement described previously.

Discussion of the Business-Environment-Customer Synergies Diagram

Using the BEC Synergies diagram to consider the challenges of integrating eco-design into the product development activities of a business has highlighted several issues which may merit further investigation.

First, it would seem logical to suggest that the objectives of (environmental) sustainable development are most likely to be met by products which fulfill 'tri-benefit' requirements as defined previously. It is suggested that aiming to create products which fulfill 'tri-benefit' requirements might make good strategic sense from a point of view of the business. This is perhaps best explained by considering the alternative scenarios.

A business which focuses its efforts on improving the product lifecycle with regard to customer and business requirements only (sector D) may have medium term success by ensuring positive and profitable relations with customers are maintained by providing products which successfully meet their requirements however in the long-term their failure to manage environmental risks may result in significant future costs to comply with environmental legislation or to rectify the environmental impacts of their products. Alternatively, a business which pursues environmental requirements to the extent that they neglect customer requirements (sector B) are soon likely to be overtaken and replaced by businesses creating products which better fulfill customer requirements. Finally, focusing efforts on meeting product requirements which only benefit the business (sector A), may result in short term gains in terms of cost savings, but it is likely to expose the business to both the aforementioned types of risk. For further analysis of the types of business context in which 'it makes sense to be green', and the types of strategies which may be appropriate in those cases, see [24].

Ascertaining the validity of this reasoning, and gauging the extent to which businesses are persuaded to act based on this reasoning, are major issues for future work. If, as is hoped, businesses do decide to focus their efforts on meeting tri-benefit requirements within the product lifecycle then they will need tools to assist them, both to highlight the opportunities and to implement a solution. QFDE is suggested as being one tool which does manage to incorporate requirements of the business, the environment and the customer to a certain extent, however, it does not assist businesses beyond this stage of the NPD process.

There therefore seems to be considerable scope for modifying existing tools or creating new tools which aim assist the business to fulfill tri-benefit requirements. Whilst such tools will be needed across the business functions, the focus of future work within the research program presented here will be on developing design tools which meet this aim and can be easily integrated into a businesses existing NPD process.

5 ACKNOWLEDGEMENTS

The authors would like to thank the businesses who participated in this study along with the Nuffield Foundation and the South West of England Regional Development Agency for their financial support of this project.

6 REFERENCES

[1] T. McAloone, N. Bey, C. Boks, M. Ernzer, and W. Wimmer, 2002, Towards the actual implementation of ecodesign in industry - the `haves` and `needs` viewed by the European ecodesign community, presented at CARE Innovation 2002, Wien, Austria.

[2] H. Brezet, C. v. Hemel, UNEP IE Cleaner Production Network., Rathenau Instituut., and Technische Universiteit Delft., 1997, Ecodesign : a promising approach to sustainable production and consumption. Paris, France: United Nations Environment Programme.

[3] T. McAloone, 2000, Industrial Application of Environmentally Concious Design. London, UK: Professional Engineering Publishing Ltd.

[4] O. Pascual, C. Boks, and A. Stevels, 2003, Communicating eco-efficiency in industrial contexts: a framework for understanding the (lack) of success and applicability of eco-design.

[5] J. Fiksel, 1996, Design for Environment - Creating Eco-efficient Products and Processes. New York: McGraw-Hill.

[6] European Commission, 2003, Directive 2002/96/EC of the European parliament and of the Council of 27 January 2003 on Waste Electrical and Electronic Equipment (WEEE), Official Journal of the European Union, vol. 46, pp. 24 - 38.

[7] European Commission, 2003, Directive 2002/95/EC of the European Parliament and of the council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, Official Journal of the European Union, vol. 46, pp. 19-23.

[8] European Commission, 2005, Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council, Official Journal of the European Union, vol. 48, pp. 29-58.

[9] O. Pascual and C. Boks, 2004, An overview of environmental product performance measurement in the Asian electronics industry.

[10] Department of Trade and Industry, 2006, Innovation Self Assessment [online], http://www.innovation.gov.uk/self_assessment/home.asp?p=assessment, (accessed: 14/04/06).

[11] K. Masui, T. Sakao, and A. Inaba, 2001, Quality function deployment for environment: QFDE (1st report)-a methodology in early stage of DfE.

[12] D. Fitzgerald, P., T. Gogoll, H.,, J. Herrmann, W., P. A., and L. Scmidt, C., 2005, Beyond Tools: A Design for Environment Process, International Journal of Performability Engineering, vol. 1, pp. 105-120.

[13] R. H. Gray, J. Bebbington, and D. Walters, 1993, Accounting for the environment. London: Chapman.

[14] J. G. Vogtlander, A. Bijma, and H. C. Brezet, 2002, Communicating the eco-efficiency of products and services by means of the eco-costs/value model, Journal of Cleaner Production, vol. 10, pp. 57-67.

[15] S. Rocchi, 2005, Enhancing Sustainable Innovation by Design, vol. Doctorate. Rotterdam: Erasmus University Rotterdam.

[16] G. Johansson, 2002, Success factors for integration of ecodesign in product development: A review of state of the art, Environmental Management and Health, vol. 13, pp. 98-107.

[17] G. Olundh, 2006, Modernsing Ecodesign: Ecodesign for innovative solutions, in Department of Machine Design, vol. PhD. Stockholm: Royal Insitute of Technology.

[18] J. Tidd, 1997, Managing innovation: integrating technological, market and organizational change.

[19] L. D. Desimone, 2000, Eco-Efficiency: The Business Link to Sustainable Development.

[20] O. Pascual and A. Stevels, 2005, Ecodesign Operationalization and Company Performance in Electronics Industry.

[21] S. Behrendt, 1997, Life cycle design: a manual for small and medium-sized enterprises.

[22] K. Ishii and A. Stevels, 2000, Environmental Value Chain Analysis: a tool for product definition in Eco Design.

[23] G. A. Keoleian, J. Koch, and D. Menerey, 1995, Life cycle design framework and demonstration projects: Profiles of AT&T and AlliedSignal, vol., N. R. M. R. Laboratory, Ed.: U.S. Environmental Protection Agency.

[24] F. F. L. Reinhardt, 1999, Bringing the environment down to earth, Harvard business review, vol. 77, pp. 149-57, 186.

NordDesign 2008
August 21 – 23, 2008
Tallinn, Estonia

A Constraint-based Approach to Sustainable Design and Development

Helen Liang, Glen Mullineux, Geoff Hammond
Innovative Design and Manufacturing Research Centre
Department of Mechanical Engineering
University of Bath
Bath, BA2 7AY
UNITED KINGDOM
H.Liang@bath.ac.uk

Abstract
Integration of sustainable design solutions is a current issue at the forefront of any business that claims to have corporate and social responsibility. Sustainable design and development stems from the idea of sustainability which is an increasingly well known ideal but with an application and resulting definition that can differ across the many different industrial disciplines. Sustainability and indeed sustainable design becomes a complex problem due to the many interlinking factors that evolve around three key principles of people, planet and prosperity.

This paper reports a research programme that aims to establish a generic interpretation of sustainability and how the complex problem of sustainable design can be effectively and efficiently tackled using a constraint-based approach. The paper discusses how different aspects of sustainability and sustainable design affect design process thinking and examines their effect on project management including a discussion of current tools such as life cycle assessment, information modelling and integrated resource management that are widely used. There is also an introduction into a newly formed concept which involves the application of a function specific constraint modeller in order to manage sustainable design and development.

Keywords: Sustainable design, integrated resource management, computer aided design, constraint modelling.

Introduction
Sustainability, in its own right, can be considered as a newly founded discipline that has evolved most prominently within the last two decades. Indeed, the term “sustainable” is increasingly used by industrial players who claim high standards of practice as part of their corporate and social responsibility. However this is suspected to be more than questionable in many cases. These suspicions are founded partly on the lack of definition and complex nature of sustainability even within the academic and scientific arena and are also due to the lack of complete and formally established tools and methods.

The complexity of sustainability itself goes much deeper than first meets the eye. Sustainable design and moreover sustainable development can be a long and arduous process which is considered as the journey towards the goal of sustainability. However, as can be seen from published literature, it has been accepted that sustainability is generally based on the foundation of three key factors: people, planet and prosperity [1]. These cover the breadth of sustainability with the onus of sustainable design based upon the planet, and this is analogous to ecodesign and the environmental aspects within design and development.

Due to the level of complexity, managing effectively the elements of sustainable design has become the focus of research detailed in this paper. Although current tools exist under the scope of computer aided design, the majority of these have not been specifically developed to encompass the full range of elements within sustainable development. It is therefore the aim of the research programme to investigate methods of using the constraint-based approach that is detailed here, in order to manage the inherently complex nature and interlinking disciplines of sustainable design and development.

Interpreting Sustainability and Sustainable Design and Development

Although the general nature of sustainability is easily understood, it took an astounding four years to establish even the most widely accepted definition in the late 1980's Brundtland Report entitled "Our Common Future". The report proposes that "sustainable development meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [2].

As a result of the Brundtland Report, additional models of sustainability have been developed in order to further define the concept. The most dominant model bases sustainability on the foundations of people, planet and prosperity. These cover generic aspects of society, environment and economics which are considered as the "triple bottom line" of a sustainable business. This often forms the basis for a company's claim of high standards in corporate and social responsibility. However, the terms of people, planet and prosperity and the consequent expressions of "society, environment and economics" are themselves considered confusing and non-self explanatory [3]. Attempts to remove such confusion have led to other models such as the so-called prisms of sustainability, shown in Figure 1. These models seek to avoid ill-defined terms whilst creating measurable indicators of sustainability to provide a holistic and satisfactory description [4].

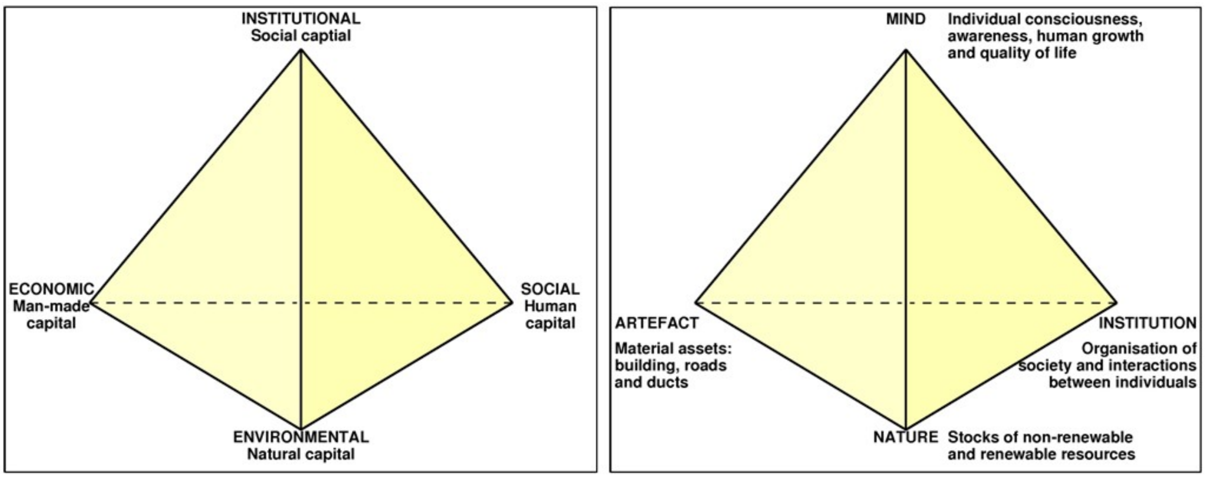

Figure 1. Prisms of sustainability

Within an industrial setting, the more holistic models, such as those detailed in Figure 1, are overlooked as they can seem overly complex. In some cases, a particular focus and hence an element dedicated to natural resources is added to the three existing baseline factors of people, planet and prosperity. The different models of sustainability only emphasise the lack of formal definitions within the emerging discipline and the numerous interlinking aspects that must be considered in design processes. From literature [3][4], it is seen that many aspects from models or definitions are in essence no different. In Figure 1, The "Environmental" and "Nature" points on the prisms represent equivalent sustainability factors.

The generic interpretation used in this paper is that sustainable development is the optimum development and contribution to society, environment and economics without compromising future needs working towards a goal of sustainability.

Sustainable Design and the Design Process

Consideration of sustainability and therefore sustainable development has its effect on the design process. It is therefore necessary to consider sustainable design and its integration into the design process which is represented in Figure 2. The design process itself seems to be the subject of much research and is well documented. It can best be defined as the "organisation and management of people and the information they develop in the evolution of a product" [5]. The process may be carried out in a series of individual or combination of consecutive and or concurrent events. Many models of the design process have been proposed (e.g. Pahl and Beitz) but most are variations on the six main activities shown in Figure 2 [6].

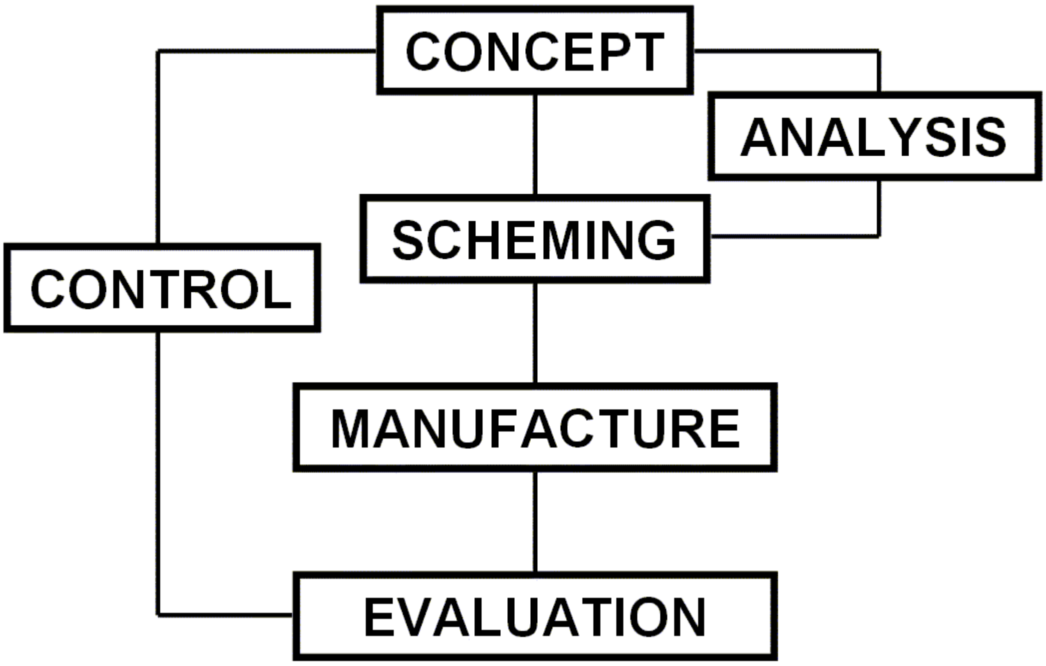

Figure 2. The design process

Research into the design process is based on continuing endeavours to improve the effectiveness of design decisions to reach an optimum solution. More recently, design has rapidly evolved as an activity primarily driven by economic factors such as profit, cost and time to market. It is now an activity also driven by environmental factors. Furthermore, the incorporation of social and environmental considerations in design is continually increasing due to the recent concerns related to sustainability and sustainable development.

The integration of environmental considerations into product design and development has led to the inception of *ecodesign* in which design decisions are based around the effects on the planet including factors such as energy consumption or depleting natural resources. It is therefore unsurprising that the onus of sustainable design and development has so far been placed upon the environmental dimension. Development of low environmental impact products, processes and systems is preferable during the initial concept stages of the design process. This demands knowledge of methodologies in design for the environment at the early concept stage. The need to understand the ecodesign methodology before executing the process applies to sustainable design and development which should also be implemented at the concept design stage of the design process.

The addition of sustainability as a consideration into design is effectively considered as a factor in the search for an optimal design solution. When incorporated into the design process, the elements of sustainable design add a significant number of considerations. This requires management of new and additional information knowledge within an already data rich process. Although there are no well known sustainable design process models, methods of sustainability appraisal have been developed under the influence of legislation such as the 2001/42/EC European Directive on the assessment of the impact and effects of certain plans and programmes on the environment. This has been largely specific to the civil engineering and construction sector.

Industry commonly labels design objectives as *key performance indicators (KPIs)* that often relate to targets and measures for success. Such indicators stem from the requirements of a product design specification and can be both qualitative and quantitative. Therefore, it is possible to objectively measure the effective level of sustainability within a design by creating a framework that appraises and evaluates key performance indicators. A sustainability appraisal framework is most likely to be effective when used at the early concept design stage. The application of such a framework is currently prominent in the civil engineering and construction industry in which sustainability has a big impact on the design process and the end result. Sustainability in this sector will involve key performance indicators such as land, buildings, people, transport, energy, water and waste management.

Methodologies and Support for Sustainable Design and Development

Examining sustainable design and its effects on design process has an impact on methodology and the tools and techniques that are inherently used. In conventional design, c*omputer aided design (CAD)* tools and systems have provided designers with increased capabilities. They have evolved to comprise three dimensional models with parametric capabilities that integrate data management, planning and manufacturing facilities [7]. Given the current interest, “intelligent CAD” systems are evolving to allow industries to assess quick measures of cost and energy and hence to help to reduce these.

The application of such CAD based tools is commonplace within industry and has led to the development of information modelling used specifically by the architecture, engineering and construction industries [8]. Specific to such consultancies, *building information modelling (BIM)* is software that generates CAD models for coordinated design and integration with mechanical, electrical and plumbing services [8]. It is also easily and readily accessible within globally distributed teams.

The advantage of such information modelling is that it allows design information to reside within one central model and can be used by all disciplines within a design team, without duplication of information. Models created are viewed with a graphical user interface, and information can be directly and readily extracted for documentation purposes. Most important, however, is the ability of the model to provide information ready for technical analysis such as finite element analysis or computational fluid dynamics with a simple application programming interface. This feature of information modelling provides a high level of interoperatability and semantic knowledge transfer. This contributes to the effective management of people and information to help develop good and sustainable design solutions that cover various design objectives.

Although these CAD tools and techniques provide effective results and offer savings in time, they have not been specifically developed to encompass the full scope of sustainable development. In some cases the qualitative and social aspects of sustainability are neglected. It is also the case that plug-ins, for example, those that provide energy analysis or computation of material and resource quantities, have been developed independently and do not always interface with different information modelling software.

Life cycle assessment (LCA) is an appraisal methodology that has evolved through the ecodesign discipline and is accepted and used throughout industry. The methodology examines the energy and resources used for production, transportation, through-life use and disposal of a product. In effect a “cradle to grave assessment”. In examining the environmental impact, improvements are made and often result in both environmental and economic savings. Although initially a time consuming exercise, the development of CAD support for the methodology has led to the development of software and therefore tools which can instantaneously chart the energy use and effects of each design decision for optimal results in the concept and scheming phases of the design process.

Constraints and Constraint Modelling as a Computer Aided Design Tool

In the same way that CAD tools have been created for LCA methodologies, there exists potential in the use of constraints and constraint modelling for supporting sustainable design and development. In design work, there are many constraints imposed upon what is possible. They are *declared restrictions* that stem from client or stakeholder demands, some from physical laws and others from legislation or guidelines. Constraints naturally arise in other areas of design and various constraint-based techniques have arisen in recent years. There has been much interest in constraint-based graphics and CAD systems where constraints are used to ensure that geometric entities maintain in the appropriate relationships to each other [9]. Particular application areas have used constraints as a means for dealing with forms of parametric design [10].

A constraint can in some instances be regarded as a relationship between some of the design parameters. It corresponds to a region of design space in which the constraint is satisfied. Different constraints correspond to different regions and a fully satisfactory design solution is one which lies in the intersection of all the regions, as suggested in Figure 3. If the design problem is over-constrained then the intersection is empty and the part of the skill of the designer is in deciding which constraints can be relaxed without jeopardising the entire design.

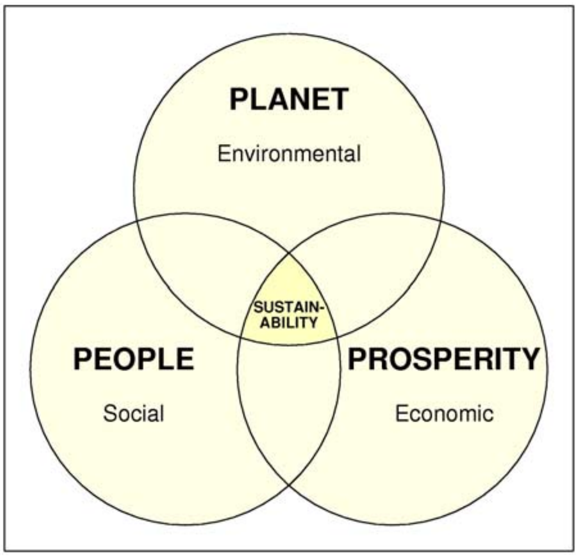

Figure 3. Design and solution space for optimised sustainable development

If constraints are available and their validity can be tested, there are several approaches that can be used. The simplest is *constraint checking*. Here each constraint is tested in turn using the current design parameters and any violations are reported. The next level is *constraint satisfaction*. Here computer support is essential and software is used to vary the design parameters in order to try to make all the imposed constraints true. In *constraint optimisation* the aim is to satisfy the imposed constraints and also optimise one or more measures of performance. For example, in machine design, constraints may be specified to ensure the parts assemble at any stage of the operating cycle. The design parameters are the sizes, positions and orientations of the parts. Then constraint checking is seeing if the parts assemble correctly. Constraint satisfaction may involve adjusting the positions and orientations of the parts so that they assemble at various stages of the operation. This allows a simulation of the operation to be obtained. Constraint optimisation is used to simulate and also to try to adjust sizes so that one or more performance measures are improved.

A constraint modelling software environment has been created [11]. This allows a user to specify design parameters and the constraints between them. It then uses optimisation techniques to vary selected parameters to search for configurations which satisfy the constraints. The constraints are regarded as expressions in the parameters which are zero when they are true: their actual values are a measure of falseness. A state of minimum falseness is sought. This has the advantage of finding some form of best compromise solution even when the imposed constraints are in conflict.

One approach with complicated designs is to use constraints to model individual elements. These are then brought together as a single collection of constraints and additional ones introduced to specify how the elements interrelate. This naturally creates a more complex system of constraints. Constraint checking is of course still possible, but automatic constraint satisfaction can become more problematic. This can be eased by taking simpler (perhaps heuristic) representations of the elements, at least in the initial stages of exploring the design space. This allows some indication of the sensitivity of the design to changes in parameters to be appreciated. More realistic constraints can be introduced as replacements once an approximate feasible design has been achieved.

Integrated Resource Management Methodology

A methodology that is currently emerging to support sustainable design and development is *Integrated Resource Management (IRM).* This is the focus of the research work reported in this paper. IRM seeks to integrate and manage the interlinking factors of social contribution, environmental integrity and economic prosperity of design solutions. Its use is predominantly applicable within the civil engineering and construction sector where designers seek solutions for the development or regeneration of sustainable communities.

IRM is a method that encompasses the full scope of sustainable development. A successful example of its early application can be seen in the case study of the Municipality of Heidelberg, Germany. The municipality initially faced the challenges of unemployment, unaffordable housing and shifting demographics that threatened the sustainability of the community. The reaction was to develop a plan that integrated the management of the many and varied methodologies for sustainable development. Techniques such as "environmental budgeting", which draw parallels to financial budgeting, were employed to manage the natural resources as economically as artificial resource, namely money [12].

Creating a consistent framework provided a structured approach to the problem which aimed to improve and maintain sustainable living within the municipality. The use of an IRM methodology completed the solution strategy allowing the successful consideration and management of financial, human and natural resources. This holistic approach is not only the essence of sustainable development, it is also mandatory.

Heidelberg is an example where IRM has been applied to improve the social aspects of a community whilst considering both ecology and economy. Better social living has been achieved whilst reducing environmental factors such as carbon dioxide emissions and residual waste. However, the success of the project is arguably dominated by the collaborative efforts of the community to draft, develop, apply and maintain the IRM framework. It is also an example where the IRM methodology can be used in an iterative manner as analysis is continuously carried out for existing and future scenarios within one consistent framework. The case study provides support for the application of the IRM methodology in managing many interlinking factors and devised key performance indicators (KPIs) for sustainable development.

A Constraint-based Approach to Integrated Resource Management

Within sustainability appraisal frameworks, such as Heidelberg, there exist objectives that are associated with key performance indicators. These are likely to be many interlinked indicators and correspondingly the objectives can be interrelated and even contradictory. Using some objectives as constraints on feasible solutions and other as targets, allows the creation of an optimisation problem with constraints. In this way it seems that there is a constraint modelling approach which can work alongside methodologies such as IRM for sustainable design and development. This adds to existing constraint-based approaches for conceptual and life-cycle design [13] [14]. For IRM, the approach has capabilities to continuously manage and capture the complex interactions of multidisciplinary key performance indicators as an appraisal and even optimisation tool for sustainable design methodology.

Investigating a Constraint-based Approach to Sustainable Design and Development

As previously suggested, constraint-based approaches deal with the limitations imposed by design constraints and seek to improve or optimise various performance measures. This suggests that such an approach is possible with relation to the IRM methodology. The limitations imposed by acceptable values of some of the KPIs imposes constraints upon what is allowable, and the desire to improve the values of other indicators means that these can act as suitable performance measures. Thus exists the opportunity to create a new methodology around IRM and generate appropriate tools that benefit both sustainable design and development and the general design process. Investigation into such a constraint-based approach is beginning with a focus on tools for the civil engineering and construction sector.

Preliminary work is examining the IRM methodology and investigating the use that has been of KPIs as reported in the literature and practical industrial case studies. These studies will be used to identify the constraints that emerge between key performance indicators and how these constraints can be used to produce optimal solutions. A constraint modelling approach will then be developed and applied with IRM methodology. Case studies and trials of an IRM constraint modeller will be carried out to investigate user interaction, benefits, drawbacks and possible limitations of the approach.

Conclusions

It has been seen that there exists an opportunity to create a design methodology and constraint-based approach to sustainable design and development. Sustainability as a discipline encompasses many variables which are shown to be effectively managed using integrated resource management. Key performance indicators obtained from design objectives and project specification translate into constraints, providing in effect, an optimisation problem for many interlinking variables.

It is intended that the research will provide a methodology to capture complex interactions between design objectives in the form of key performance indicators. These will be specified by the civil engineering and construction sector with a focus on sustainable design and development. However, it is anticipated that the research outcome will provide a general application for any design discipline.

The constraint-based approach can provide a methodology and the constraint modelling technique can form a sustainability appraisal tool. Its primary function will be an information exchange and informed decision making tool that brings together the interlinking disciplines of sustainable design and the multidisciplinary experience of those working to achieve sustainability.

Acknowledgements

The work reported in this paper is being undertaken within the EPSRC funded Innovative Design and Manufacturing Research Centre at the University of Bath. Financial support for the first named author is provided by the Centre and by Arup. This support is gratefully acknowledged.

References

[1] Hammond, G. P. and Winnett, A. P., “Interdisciplinary perspectives on environmental appraisal and valuation techniques”, Proceedings of the Institute of Civil Engineers, Waste and Resource Management, Vol. 159, Issue WR3, 2006, pp.117 – 130.

[2] World Commission on Environment and Development, “Our Common Future”, Oxford University Press, Oxford, 1987.

[3] Kain, J–H., “Urban Support Systems, Social and Technical, Socio–Technical or Sociotechnical?”, Thesis for the Degree of Licentiate of Architecture, Göteburg, Sweden, 2000.

[4] Keiner, M., “History, Definition(s) and Models of Sustainable Development”, Elektronische Daten (electronic data), Eidgenössische Technische Hochschule (ETH), Zurich, 004995678, 2005.
[5] Ullman, D. G., “The Mechanical Design Process”, Second Edition, McGraw–Hill, ISBN 0-07-065756-4, 1997.
[6] Medland, A. J. and Mullineux, G., “CAD: A Course Book”, Kogan Page, 1988.
[7] Singh, B., Mathews, J., Mullineux, G. and Medland, A.J., “Embedding general constraint resolution into a CAD system”, Proceedings of Design 2006, Dubrovnik, Croatia, 2006.
[8] Senescu, R., Mole, A. and Fresquez, A., “A case study in structural drafting, analysis and design using an integrated intelligent model”, Proceedings of Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montréal, Canada, 2006.
[9] Martínez, M. L. and Félez, J., “A constraint solver to define correctly dimensioned and over-dimensioned parts”, *Computer-Aided Design*, 2005, pp.1353–1369.
[10] Rudolph, S. and Bölling, M., “Constraint-based conceptual design and automated sensitivity analysis for airship concept”, *Aerospace Science and Technology*, 2004, pp.333–345.
[11] Hicks, B. J., Medland, A. J. and Mullineux, G., “The representation and handling of constraints for the design, analysis, optimization of high speed machinery”, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)*, 2006, pp.313-328.
[12] Kepran, H., “Heidelberg: Creating a Framework for Integrated Resource Management”, International Council for Local Environment Initiatives, Case Study 78, ICLEI, Canada, 2002.
[13] O’Sullivan, B., “Interactive constraint-based conceptual design”, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)*, 2002, pp.303-328.
[14] Yan, X. And Sawada, H., “A framework for supporting multidisciplinary engineering design exploration and life-cycle design using underconstrained problem solving”, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)*, 2006, pp.329-350.

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

EXTRACTION AND ANALYSIS METHODOLOGY FOR SUPPORTING COMPLEX SUSTAINABLE DESIGN

Helen Liang[1] and David Birch[2]
(1) University of Bath, UK (2) Imperial College London, UK

ABSTRACT

The advent of computer-based tools in design has meant ever larger sets of parameters can be taken into consideration. It also means other factors associated with environmental issues can be considered and increasingly there are legislative requirements to do so. This means increasing demands are placed on designers to create high quality, innovative, sustainable solutions to satisfy many stakeholders. Design by nature is a complex interdisciplinary practice. Managing complexities requires the support of specifically created tools and methods to handle a large number of design parameters. This is particularly true of the built environment where such parameters include the spread of buildings, energy consumption, handling of waste, management of water and transport needs. The paper discusses a methodology that seeks to support the decision making process and design optimization for complex designs, demonstrating an approach for dealing with integrated assessments and optimal design choices. It is based upon automatically studying relations between design parameters so that interdependencies can be obtained, related parameters can be clustered and sensitivities established.

Keywords: sustainability, built environment, model extraction, sensitivity analysis, design optimization

1 INTRODUCTION

In the current climate, the issues surrounding sustainable design are those which many disciplines are responding to with increasing vigor. Sustainable design is complex. It demands a holistic approach and necessitates decision making and strategy integration at a very early stage of the design process. It also demands compliance with details at a micro level. An abstract approach cannot be undertaken especially in the circumstances with data that is inherently highly contextual and highly integrated. The design process becomes reliant on the explicit contribution of data provided by designers with specialist expertise which is fully comprehensive in terms of data aggregation. Increasingly, the demand on detailed data is becoming more evident as part of the earlier stages within the design process.

The last decade has seen an increase in design tools, supporting methodologies and frameworks for sustainable design that are used as part of a business need for companies to be environmentally responsible. While there are guidelines for assessment methods and policy development, there is little readily available instruction on managing the actual complexities and sheer volume of detail at a complex level. An example, particularly apt, can be found within the built environment sector where current practice does not always have easy access to appropriately integrated analytical tools to inform sustainable decision making for projects at all scales [1].

Existing tools, both qualitative and quantitative, are in many cases dependent upon the knowledge base of the user. For this sector, but also design in general, there is often an emphasis on tools that are more quantitative in order to support design decisions and achieve measurable design targets. Within a multidisciplinary network, the stakeholders other than the clients themselves include the specialists that provide and formulate the data within the design process.

1.1 Sustainable Design for the Built Environment

For the built environment, the contribution to sustainable development has a large impact as buildings, through their operational greenhouse gas emissions, account for one third of the energy demand in Europe [2]. In fact, there is increasing effort to research sustainable development methods and push the boundaries of science and engineering applications in order to drastically reduce energy consumption and greenhouse gas emissions in general.

Professionals within the planning and built environment sector are constantly required by the defining nature of sustainability to consider and satisfy the demands of a wide range of stakeholders. Design within this sector requires the expertise of many specialist disciplines and it has been proposed as being ‘the most multidisciplinary practice in all of the design professions’ [3]. Within the built environment, the issues of sustainable design compound the complexities within the discipline of masterplanning.

1.2 Built Environment Masterplanning

Masterplanning in a non-statutory sense is the process which can be interpreted as the entire program of activities within a particular project. Such activities include integrated service provisions ranging from the preparation, conceptual design and detailed design through to the construction and use of a built environment.

Masterplanning and the development of masterplans, are heavily reliant upon the expertise of designers and the technical specialists from various disciplines who may use a combination of tools and methods to support their own data capture for different design scenarios.

Integrated assessments are used to actively monitor and evaluate the interactions and integration of multidisciplinary data capture. They not only give an instantaneous measure of how sustainable a scenario may be, they also form part of a natural optimization method through iterative design and analysis. In essence, each iteration increases the designer’s incremental knowledge of the design problem and contributes towards an eventual optimized design proposal.

A key stage in any design optimization activity is to understand the influencing factors that may have varying effects, large or small, on a design. Such factors, which may be considered as design variables, have different levels of sensitivity that contribute to the overall design. Examining the sensitivity of design variables is considered as an important activity in any optimization process and has its place in good design practice. Sensitivity analysis of such variables is considered an important activity in such design and has therefore formed a key part of the research reported here.

Section 2 discusses integrated resource management (IRM), an integrated assessment tool and approach increasingly used in current masterplanning activity. Section 3 provides a design strategy created on the foundations of IRM methodology. This involves the extraction and sensitivity analysis of design variables as key process activities. Section 4 gives an industry case study as an example of the applied methodology and the last section provides an evaluation and concluding remarks.

2 INTEGRATED RESOURCE MANAGEMENT

Integrated resource management (IRM) is an emerging design support tool that has the capability to support design, planning and decision making on a complex level such as urban masterplanning which runs alongside sustainability appraisal and assessment methods [4]. IRM itself has its roots and main associations within the management of natural resources such as water.

2.1 Masterplanning Design and Assessment Frameworks for IRM

Within masterplanning, sustainability assessment frameworks are created and increasingly legislated in order to support effective sustainable design. These design and assessment frameworks often make use of metrics or performance indicators in order to assess, compare and guide improvement of design proposals and design solutions [5]. Since masterplanning is a multidisciplinary activity, many disciplines will contribute their own data to the metrics and performance indicators that are developed within such frameworks. These are also often considered as a fundamental preceding activity in the development of IRM tools.

The key motivation for an IRM tool is to aggregate information from the different technical design streams into one common data model for easier accessibility and assessment. As a standalone tool, this then enables the different disciplines to produce an augmented but more importantly an integrated set of metrics for assessing masterplans for a built environment. For illustration, an assessment framework and accompanying IRM model for the masterplan of an urban development may consider, contain and represent data obtained from several disciplines. These may include those that specialize in carbon and environmental footprinting, energy strategists, water management, the handling of waste, transportation requirements, materials used in construction, the social mix of communities, and the quantity and mix of landuse.

Owing to the nature of masterplanning, there is a constant challenge between the different disciplines involved to integrate their individual design strategies. Designers and planners must consistently acknowledge and resolve the issues or conflicts that occur when accounting for complex interrelationships between design parameters of different disciplines and resource streams. In such a multidisciplinary activity this has previously been difficult to do. Such complex and increasingly numerous interrelations of design inputs often lack transparency and there often exists a complex cascade of data effects, thus pointing to the need for better data management and modeling tools [1, 6].

2.2 IRM Models

An IRM model developed by engineering and design consultancy firm Arup, as a quantitative urban metabolism tool for use in eco-city masterplanning, is considered and adapted for study. The model and tool itself, allows neighborhood, city or regional plans and policies to be developed and prioritized in the context of the relevant integrated resource streams [1]. Figure 1 shows a generic example of some common inputs and outputs, and some of the technical disciplines that provide captured data along with examples of graphical outputs. Key data and metrics used within any typical IRM model forms a mass of design input variables which can be interpreted via many different outputs. Any specific outputs may be interpreted as a key performance indicator (KPI) in which a KPI's value can be treated as a design parameter and therefore forms one or part of the overall design objectives.

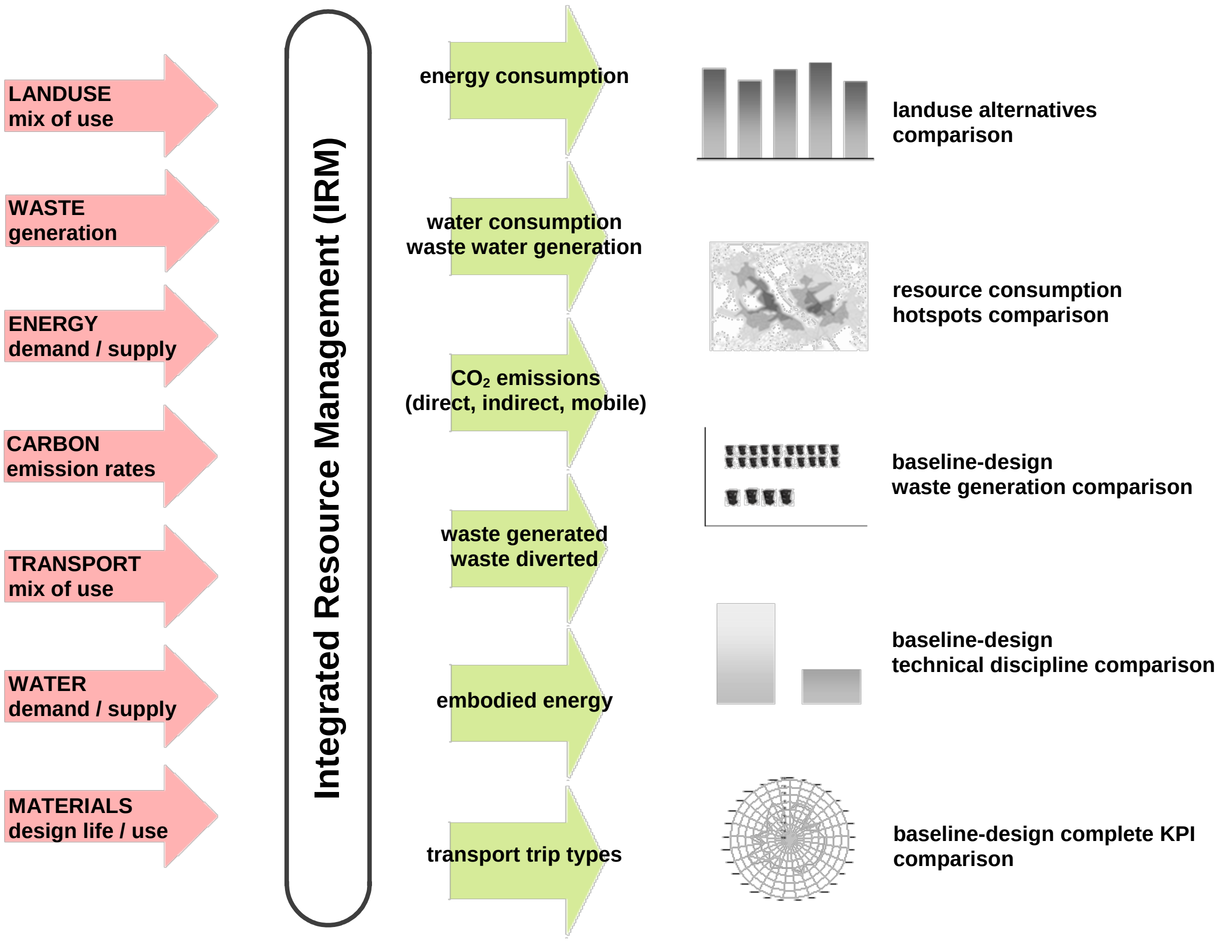

Figure 1. An Overview of the IRM Data Flows within a Model [1]

In general, many design activities and created models evaluate and provide the necessary integrated assessments for design scenarios and strategies. These evaluations are based on the declared objectives and parameters which are interpreted, in many cases, through a series of calculations using both captured data and databases of information. A large number of associated variables (in the order of thousands) are handled within such a process.

IRM models are in commercial use due to their capabilities to explore synergies, feedback loops and trade-offs for different design proposals. Since complexities exist within the relationships of the many design variables, there also exists a need to efficiently manage the large volume of data in order to produce optimum strategies and scenarios for masterplan options. This can be done using extraction of model data and sensitivity analysis which forms the foundation activities of the created methodology discussed in the next section.

3 EXTRACTION AND ANALYSIS METHODOLOGY FOR DESIGN SUPPORT

A methodology to support the use of IRM models and the decision making process for masterplanning built environments is now described. It is intended that this methodology exist alongside current supporting models and has the capability to become an integral part of sustainability assessments and other associated appraisals.

Within this, the extraction and analysis methodology (EAM) has been created with the aspiration of enabling designers or, more specifically in this paper, the planners within the built environment to better understand and manage the complexity within their assessment models. It also enables a more efficient and focused approach to design and optimization. The methodology and the defining activities are summarized in Figure 2 and explored in the following sections.

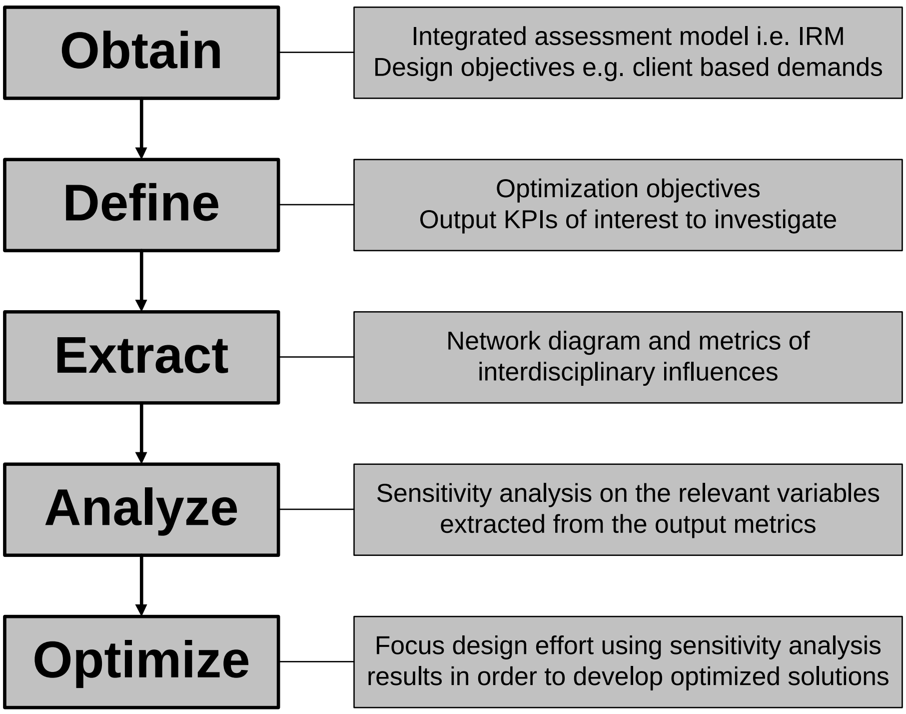

Figure 2. Extraction and Analysis Methodology (EAM) Overview

3.1 'Obtain' and 'Define'

In many disciplines, some form of integrated assessment model is created in order to evaluate particular aspects for a design or part thereof. These may be potential solutions, different cases or scenarios and initial conditions or design boundaries. Such models are then used as part of solution search and discovery and design optimization. This activity of integrated assessment has become the foundation of the methodology. IRM models are an example of an integrated assessment tool created to assess and develop masterplan strategies and scenarios for implementation. Such a model holds a large volume of highly integrated and complex data.

Obtaining an assessment model, necessary data and the key design objectives falls under the activities of 'obtain' and 'define'. In the early stages of the methodology, it is important to explicitly confirm either the optimization objectives and/or the output KPIs of interest in order to correctly focus the activities within the latter stages of the process. In fact, the majority of which, are commonly defined and described within the accompanying design and assessment framework generally laid out in the early stages of design effort.

In the case of the research reported here, a complete assessment model was obtained and adapted as part of an industry case study. However, it is conceivable that an assessment model may be created as opposed to obtained. The stages of ‘extract’ and ‘analyze’ which are discussed further in the following sections contribute to the ‘optimize’ activity which allows the ‘facilitator’ of EAM to focus their design effort or optimization with confidence.

3.2 ‘Extract’

The aim of extraction within the methodology is to disseminate understanding of specific aspects of an assessment model relevant to a specific optimization objective, output KPI or general area of interest. At the same time, this enables data handling at a more manageable level. From the assessment model, the output KPI then has its formula extracted, i.e. the path of its calculation. The extraction tool evaluates the interaction of every variable contributing to the output being investigated. The connections between all variables can then be displayed graphically as a network diagram using a custom viewer, developed for the GraphML format, in many different layout forms which each has its own benefit depending on what is required. Using the custom viewer allows insight into the complexity in terms of the sheer volume of variables, their context, and the detail of their interconnections.

The tool developed for the extraction activity not only provides an interactive and instantaneous means for visually investigating the scope of interconnections between variables across boundaries of different disciplines, there is also a series of metrics that are calculated. These metrics have been built into the extraction tool in order to further contribute to the advantages of design illumination and focus of design effort discussed further in Section 3.3. The extraction metrics are listed below.

- **Variable count and distribution** – metrics that detail the total variables contributing to the KPI under investigation and the distribution of variables with respect to the disciplines of their origin. It also details the variables that are most frequently used in any calculation paths.
- **Independent variable count and distribution** – metrics that detail the total independent variables and the distribution of these with respect to the disciplines of their origin. Such variables are explicitly not obtained from calculations within the assessment model itself and are strictly inputs only. The most frequently used independent variables are also reported.
- **Reference count and distribution** – metrics that detail the total connections made between variables and the average number of references made with respect to the disciplines of their origin within the assessment model.

The counts and distributions for variables, independent variables and references provide insight into the complexity of the assessment model and the distribution of data. This is not only with respect to the KPI in question but also to the disciplines involved. For example, it is possible to look at the distribution and origin of variables that extend from the mix of landuse and how they might interact and effect water management, handling waste and energy strategy solutions.

In addition to these evaluated metrics, the connections between different disciplines are examined and detailed through a summary matrix which provides insights into interdisciplinary influences and how they interact. Three different summaries can be provided.

- **A direct reference matrix** – this details the references made between each variable from one discipline and all other relevant disciplines. This demonstrates the disciplines that are connected and the frequency of such connections.
- **An independent direct reference matrix** – this details the references only made between each independent variable from one discipline and all other relevant disciplines. This demonstrates the disciplines that are connected and the frequency for independent variables only.
- **An indirect reference matrix** – this details the indirect references made between each variable from one discipline and all other relevant disciplines. This demonstrates the extent of variable interaction, potential locations for effects of changes and the complexity within the entire model.

The next stage of the methodology uses a sensitivity analysis tool. Although the extraction and the metrics provide key insights and valuable information to widen the knowledge base of the planners, the sensitivity analysis requires only information based on the independent variables.

3.3 'Analyze'

Sensitivity analysis is an activity employed in numerous mathematical and scientific fields and has significant benefits in interpreting and managing large and complex data networks. For the built environment, sensitivity analysis can reduce the corresponding volume of data and design effort for 'robust assessments of impact' [7].

The primary function of such an analysis is to determine how a model's specific output responds to changes to input variables. It is therefore possible to determine which variables hold more dominance when interpreted as design parameters and ultimately their contribution to one or more design objectives. Carried out as a series of experimental runs, variables are altered under specific conditions. The design of such sets of experimental runs relates to the area of Design of Experiments (DoE) [8].

There exist numerous types of experimental design which vary in efficiency and the insight provided when investigating the sensitivity of a model. These can be grouped under two main approaches. In the first instance, single variance analysis involves the variation of an individual variable for evaluation against a single output. In the second instance, multiple variance analysis involves the variations of several variables for evaluation against one or more outputs. This paper deals with multiple variance analysis.

Sensitivity analysis itself carries a certain amount of subjective influence dependent on the chosen methodology applied and the explicit data values specified to populate a model. Within complex models such as the IRM, boundaries and limitations exist which are often only tacitly understood. These must be acknowledged and interpreted for sensitivity analysis in terms of upper and lower limits of variation that can be described as confidence intervals [9].

Regardless of the design of experiment, sensitivity analysis provides scope for design space exploration and scenario or solution refinement contributing to good general design methodology. There are four key advantages to carrying out a sensitivity analysis.

- **Designer illumination** – sensitivity analysis has the ability to show both variable dominance and interaction. This indicates which outputs are most sensitive and the variables that affect this change. Continuous analyses on design iterations also increase the knowledge of overall responsiveness of outputs to the input variables.
- **Reducing the problem space** – in assessing which variables have more or less dominance, it is possible to narrow the scope of the problem space. Certain assumptions may be tested and this may regard variables as being entirely ineffective or effective within a model. It can also demonstrate potential conflicts between variables and outputs.
- **Focusing design effort** – the results of the sensitivity analysis provide the designer with increased knowledge of the potential design solution space and contributing factors. Hence, it allows the designer to focus efforts on specific areas of relevant interest and the variables that have the biggest scope for effect.
- **Design optimization** – sensitivity analysis contributes to an optimization process for design in general and also provides scope for multi-objective optimization. It is possible to look at specific variable effects on not one but many aspects of specific design objectives simultaneously. This increases knowledge not only of variable behaviour but also of outputs within the system.

Due care must be taken when carrying out a sensitivity analysis especially when there exist interactions between a large number of variables. These interactions are not always immediately obvious when considering the inputs and outputs that are part of an applied sensitivity analysis. For example, consider the space occupied by a certain shape with the basic input variables of height, width and depth. The output of volume is sensitive to these variables individually but in reality the output is far more sensitive to their interactions, which are some multiplication of the three variables together. When considering a large number of variables, there is an explosion in the number of interactions to consider which means that carrying out a full sensitivity analysis may be prohibitively time consuming and computationally expensive. This is especially the case with an IRM model that contains thousands of variables alongside several tens of output KPIs. Ideally, each combination of design variables, along with every possible interaction, should be tested against the relevant design objective. This process is an example of experimental design known as a factorial design. There exist many techniques which carry out sensitivity analysis and handle the complexities that occur in factorial design.

The computational cost of analysing many more than ten variables, as with IRM, means such analysis begins to become increasingly intractable. For this reason, more efficient designs have been developed such as PB designs [10]. First reported by Plackett and Burman, PB designs are among the computationally least expensive but lack insight into the interactions between variables. The method has linearity in the number of experimental runs compared to the number of variables, this makes a PB design relatively inexpensive in terms of the computational effort [10,11]. The main usage of PB design is when the number of variables under consideration or the duration of each experiment (i.e. the number of analysis runs) means that the primary consideration in design choice is computational efficiency. This is the case and reason why PB design has been applied alongside the IRM model in the research reported here as a large number of variables are being considered and managed.

The extraction tool actually has the capability to run without any real data since it simply extracts the relationships and/or calculations established in the model for processing input data. However, the sensitivity analysis tool developed from PB design techniques explicitly requires an integrated assessment model with real data inputs. During the analysis, the tool is constantly reading and writing values into the assessment model in order to test for the sensitivity of the variables. The independent variable count and distribution metrics directly prescribe the input variables for analysis. There are three prerequisites required for setting up each of the variables investigated.

- **An interpreted description** for each variable so that it is fully comprehensive with respect to the project as certain variables may exist only as a series of shorthand expressions.
- **A specified default value** that is relevant and realistic. This value may be zero, estimated, or an initial value depending on the purpose of the sensitivity analysis and the user experience.
- **A specified confidence interval** bounding each variable with a high or low value. This may be expressed either as a percentage of the specified default value or numerically.

The interpreted description and specified default value is in most cases, directly obtained from the assessment model. Due care must be taken when bounding each variable with its confidence interval as the sensitivity analysis is most effective and yields the best results when its variables can be investigated over their widest possible range. Setting the interval may require knowledge and experience specific to a technical stream or discipline. It also involves a certain level of intuition and tacit knowledge in order to set the correct realistic context for the sensitivity analysis.

The result of the sensitivity analysis is a list of variables tested and ordered according to which the output (KPI) is most sensitive to changes in. The absolute values in this list are numeric and normalised within the tool for interpretation and then rated on a scale from zero to one-hundred. In the sensitivity tool itself, a variable that has high dominance has a value of one-hundred where as a variable with zero dominance has a value of zero.

When examining the results of the sensitivity analysis, the general shape of the list indicates whether certain variables have dominance on the output under investigation. There may be variables that have substantial dominance individually or as a group of variables. It is important to note that beyond a certain point in the list, all variables have similar sensitivity values. At this occurrence, it is not sensible to interpret the figures since their effects are not significant enough to be able to differentiate them from potential aliasing effects.

Following the sensitivity analysis, the designer gains valuable insight into the most dominant variables within a design set and/or scenario, the user of the tools and overall methodology can take the results in order to demonstrate those variables that have the most dominance in the overall design solution so that design iterations may be focused on varying those that are most influential. It also sets the scope for awareness of design constraints and design compromise since variables that may be more dominant to one variable may have less influence on another when considering a different output KPI.

3.3 'Optimize'

Over the course of a design process, the output KPIs are effectively used as optimization goals within the design and planning process. Where an assessment model such as IRM is in use, it is possible to define an optimization problem in such a way that inputs from many different disciplines may be varied so as to optimize the output KPIs calculated by the assessment model. Using this approach, KPIs established in the initial stages of the process may be interpreted as design constraints [12] and general optimization techniques such as direct search and gradient methods [13] may be applied.

Design improvement and optimization in masterplanning within the built environment sector is essentially a process that is often heavily reliant upon designer intuition as precedent-based design [5]. Whilst different scenarios are set up with changes in variables, it is the result of each iteration that provides illumination for the design decisions made in order to reach potential design solutions so that undesirable designs or scenarios are slowly funnelled out.

The extraction and analysis methodology has the capability to support a wide range of decision support tools and provides the initial setup for optimization. The 'optimize' activity is used to automatically adjust the relevant variables for a design solution.

4 INDUSTRY CASE STUDY

Using the created extraction and analysis methodology (EAM), the tools and techniques were applied to a case study which considers an eco-city masterplanning development for the scenario of a highly populated urban area of 7,500,000 square meters. An IRM model was developed for the study which modeled a series of KPIs and provided an integrated assessment of a design scenario based on inputs from several technical disciplines. As a performance indicator, the KPI representing carbon emissions was selected as that of interest in this study. The results are presented in the following tables.

Table 1. Extraction metrics

Metric Details / Description	**Count**	**Percentage Distribution of Metric Data (%)**					**Most frequently used variable**
		landuse	transport	water	energy	other	
Variable count / distribution	2357	2	30	16	40	12	1. energy demand 2. water demand
Independent count / distribution	1117	2	25	17	41	15	1. energy demand 2. residential land
Reference count / distribution	3404	3	8	5	17	N /A	N /A

Table 1 shows the results of the extraction on the variables within the case study model. These represent a selection of the results for four key disciplines of landuse mix, transportation, water management, and energy consumption. All other disciplines are grouped into the last section for percentage distributions of the variables.

Table 2. Reference Matrix of Direct Variable References

Percentage Distribution of Direct References (%) (3404)	from\to	landuse	transport	energy	water
	landuse	0.5	0	2	0.4
	transport	0	29	2	0
	energy	0	0	37	0
	water	0	0	0.1	16

Table 3. Reference Matrix of Independent Direct Variable References

Percentage Distribution of Independent References (%) (1516)	from\to	landuse	transport	energy	water
	landuse	8	0	1	4
	transport	0	24	2	0
	energy	0	0	25	0
	water	0	0	0	12

Table 4. Reference Matrix of Indirect Variable References

Percentage Distribution of Indirect References (%) (41,068,458)	from\to	landuse	transport	energy	water
	landuse	< 0.01	0	1	< 0.01
	transport	0	< 0.01	0.4	0
	energy	0	0	28	0
	water	0	0	10	< 0.01

Table 2 demonstrates the percentage distribution of the total number of references made from one discipline to another directly, whilst Table 3 demonstrates the same distribution for independent variables. Table 4 demonstrates the distribution of the total number of references made from one discipline to another indirectly. The total number of references is listed in the left hand column of each reference matrix and the same disciplines are reported as in Table 1.
The results from the extraction indicate that energy as a discipline contributes the largest number of variables towards the KPI of carbon emissions. The 'energy demand' variable from this discipline is also most referred to within the assessment model as well as being the most frequently used in calculating an assessment for total carbon emissions. The frequency of the 'water demand' variable in total variables and 'residential land' variable in total independent variables also demonstrates that these are particularly involved in calculations for carbon emissions. In addition, demonstrating the total number of references may be considered as a direct correlation to the complexity that is handled within each discipline for the specific output KPI of carbon emissions. It also demonstrates the capability of the IRM model to efficiently manage a large number of interlinked and complex variables in order to support design decision making.
From the generated extraction metrics, the list of independent variables was carried forward for use with the sensitivity analysis tool. Alongside the distribution of variables and the most frequently used variable, the sensitivity analysis provided a perspective on the variables that hold the most dominance. Table 5 provides an indication for the percentage of variables that have a very high, moderate and low dominance with respect to the disciplines previously detailed. These results then provided a design focus in which those variables that demonstrated a high dominance were examined more closely in an effort to optimize the KPI for carbon emissions and further understand their influence.

Table 5. Sensitivity Analysis Distribution of Dominance

Technical Discipline	**Distribution of Variable Dominance (%)**		
	High	**Moderate**	**Low**
landuse	17	41	42
transport	2	68	30
energy	12	62	26
water	4	81	15

4.1 Translational Applications

The approach presented is within the scope of the built environment for architecture, engineering and construction industry but the tools and methods may be applied in general design activity and transferable to different design themes. Overall, the aim of the extraction and analysis methodology is to gain an understanding of design variables, the parameters, and their relationships to specified objectives. This understanding then seeks to guide the designer to an optimized scenario in which decision support is made. Since bespoke assessment models can be easily created for the variables of any product and/or system design and, the other tools used in the methodology are established, it is conceivable that translational application exists.

5 CONCLUDING REMARKS

The tools developed within the methodology of extraction and analysis (EAM) provide a set of metrics for an approach that commercially uses IRM as an integrated assessment tool complemented by an assessment framework. These metrics clearly demonstrate the complexity held within such IRM models but also provide insight into the interdisciplinary nature of the design variables demonstrating the extent of interacting disciplines. This insight allows optimization and indeed general design solutions of certain objectives to become more manageable. Design in the built environment involves the demand, on designers and planners, to consider an ever increasing and large number of design variables that must satisfy the many design objectives and stakeholders. In masterplanning, design is both a multidisciplinary and interdisciplinary practice and managing complex data from several technical streams is difficult. The EAM and its associated tools proposed and reported in this paper provide support for the use of IRM in masterplanning. The key contribution of this work is the ability of the method and tools to transparently demonstrate and manage the complexities and interdependencies within integrated data to direct design focus for complex sustainable design.

REFERENCES

[1] Ayaz E. and Levitas J. Spatially linked integrated resource management (IRM): A tool to inform eco-city planning. In *Proceedings of the 8th International Eco-city Conference, Eco-city 08*, December 2008

[2] De Meester B., Dewulf J., Verbeke S., Janssens A. and Van Langenhove H., Exergetic life-cycle assessment (ELCA) for resource consumption evaluation in the built environment. *Building and Environment*, 2009, pp.11-17

[3] Garner S. and Mann P. Interdisciplinarity: perceptions of the value of computer-supported collaborative work in design for the built environment. *Automation in Construction*, 2003, pp.495-499

[4] Page J., Grange N. and Kirkpatrick N. The integrated resource management (IRM) model - guidance tool for sustainable urban design. In *25th Conference on Passive and Low Energy Architecture, PLEA08*, October 2008

[5] Clevenger C.M. and Haymaker J. Framework and metrics for assessing the guidance of design processes. In *International Conference on Engineering Design, ICED'09*, 2009, pp.411-422

[6] Jakeman A.J. and Letcher R.A. Integrated assessment modelling: features, principles and examples for catchment management. *Environmental Modelling & Software*, 2003, pp. 491-501

[7] Hohler N. and Moffatt S. Life-cycle analysis of the built environment. *Sustainable building and construction.UNEP Industry and Environment*, 2003, pp.1721

[8] Montgomery D.C. *Design and Analysis of Experiments*, 2004 (John Wiley & Sons)

[9] Taylor M. What is sensitivity analysis? *Health Economics*, 2009, Hayward Group Ltd

[10] Plackett R.L and Burman J.P. The Design of optimum Multifactorial Experiments. *Biometrika*, 1946, pp.305-325

[11] Yi J.J., Vandierendonck H., Eeckhout L. and Lilja D.J. The exigency of benchmark and compiler drift: designing tomorrow's processors with yesterday's tools. In *Proceedings of the 20th Annual International Conference on Supercomputing, ICS 06*, 2006, pp.75-86

[12] Liang H., Mullineux G. and Hammond G. A constraint-based approach to sustainable design and development. In *Proceedings of NordDesign 2008*, 2008, pp.181-189

[13] Papalambros P.Y. and Wilde D.J. *Principles of Optimal Design: Modelling and Computation*, 2000 (Cambridge University Press)

Contact: Helen Liang
University of Bath
Department of Mechanical Engineering
Bath, BA2 7AY, UK
Tel: +44(0)1225 385937
Email: h.liang@bath.ac.uk

Helen is a PhD candidate in Mechanical Engineering at the University of Bath. She is currently researching constraint-based approaches for design and has an academic degree in Innovation and Engineering Design. Her research is gratefully funded by Arup and the Engineering and Physical Sciences Research Council (EPSRC).

Multidisciplinary Engineering Models: Methodology and Case Study in Spreadsheet Analytics

David Birch[a] *, Helen Liang[b], Paul H J Kelly[a], Glen Mullineux[b],
Tony Field[a], Joan Ko[c], Alvise Simondetti[c]
[a] Imperial College London [b] University of Bath [c] Arup
* David.Birch@Imperial.ac.uk

Abstract

This paper demonstrates a methodology to help practitioners maximise the utility of complex multidisciplinary engineering models, an area presenting unique challenges. As motivation we investigate the expanding use of Integrated Resource Management (IRM) models which assess the sustainability of urban masterplan designs. IRM models reflect the inherent complexity of multidisciplinary sustainability analysis by integrating models from many disciplines. This complexity makes their use time-consuming and reduces their adoption.

We present a methodology and toolkit for analysing multidisciplinary engineering models implemented as spreadsheets to alleviate such problems and increase their adoption. For a given output a relevant slice of the model is extracted, visualised and analysed by computing model and interdisciplinary metrics. A sensitivity analysis of the extracted model supports engineers in their optimisation efforts. These methods expose, manage and reduce model complexity whilst giving practitioners insight into multidisciplinary model composition. We report application of the methodology to several generations of an industrial IRM model and detail the insight generated, particularly considering model evolution.

1. Introduction

To demonstrate the challenges of multidisciplinary engineering models, we consider those within the urban masterplanning community. Urban masterplanning is the process of creating a coherent design for the development of a campus, suburb, city or region. It spans not only architecture but the disciplines involved in the implementation of changes to the built environment such as acoustics and water supply.

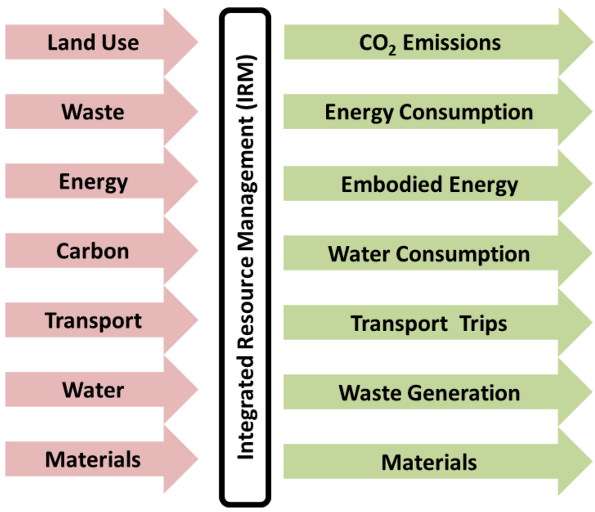

Figure 1 Conceptual model of an Integrated Resource Management (IRM) Model [Ayaz08]. Sustainability models from many disciplines are integrated to form a coherent model for assessing urban masterplans [Page08].

Increasing requirements for managing environmental impact have led to demand for interdisciplinary modeling of sustainability metrics such as annual per capita carbon emissions in order to benchmark and improve designs. These drivers have been unified by Integrated Resource Management (IRM) models [Kepran, 2002; Ayaz, 2008; Page, 2008] which integrate models from each discipline into a coherent assessment tool. Such models are commonly implemented in spreadsheet form for ease of construction, modification and portability amongst practitioners. While many benefits are realised by an integrated spreadsheet based model, there are some inherent difficulties common to many engineering models; these motivate this work and are discussed in the next section. This paper presents the following contributions to address these issues.

- We present a methodology and tool suite for systematic, automatic analysis of large spreadsheet-based models with novel metrics to assess internal communication and integrated sensitivity analysis to aid practitioners in optimisation.
- We apply this methodology with a focus upon multidisciplinary engineering assessment models, a model type not widely studied within literature.
- We demonstrate the methodology's application through practical case studies with an industrial multidisciplinary sustainability model, identifying insight for practitioners and study model evolution over three model generations.

2. Motivation

In this paper we consider Arup's IRM model [Ayaz, 2008; Page, 2008] as an example of a complex spreadsheet based interdisciplinary engineering model. We now consider some of the difficulties inherent to such models.

As shown in Figure 2, Arup's IRM model consists of several different discipline specific sub-models including energy demand, energy supply, passenger transport and land-use. Each discipline has a data input model and an output model which calculates sustainability metrics such as annual energy demand. These input/output model pairs strongly rely, not only, upon each other, but also upon the other disciplines' input and output models. For example, the energy supply sub-model uses inputs from the land-use input sub-model and the outputs of the energy demand model.

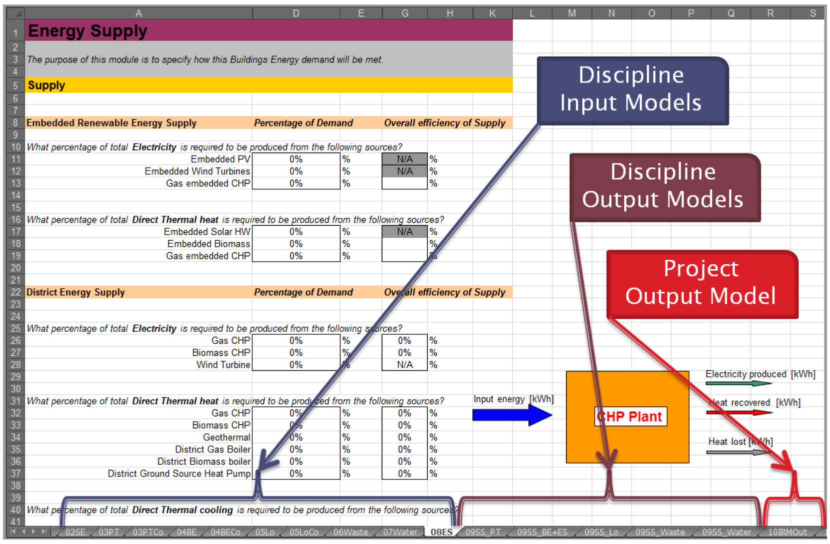

Figure 2 Arup's IRM model [Page08], is implemented as a Microsoft Excel spreadsheet. Each discipline has an input and an output model in its own worksheet. A single project metrics dashboard is provided.

This creates a complex interrelated web of models which reflects the physical complexity of sustainability concerns. In the centre of this web is a project-specific sustainability dashboard calculates summary metrics using information from all disciplines' input and output models. This complexity is a requirement of faithful modeling and is a common feature of many engineering analysis models. This class of models, in contrast to more traditional spreadsheet based models such as tax calculators, face particular challenges:

- **Model Complexity** - Such models are by their nature complex due to the strong coupling between already intricate discipline models which must become facsimiles of real life complexity. This leads to difficulty in gaining an accurate overview of the whole model and to understanding how a single discipline's model functions; especially outside of a practitioner's area of expertise.

- **Data Requirements -** Due to this complexity, engineering models frequently contain large data requirements. Our analysis identified 933 (see Section 10) separate design or analysis variables required for the carbon calculation of Arup's IRM model, ranging from the total floor area of residential buildings to the CO_2e emissions for disposing of electronic equipment. The time taken to gather, process and enter the required information is a major cost in applying such models.
- **Implicit Knowledge -** Such engineering knowledge is difficult to formalise, being built up as an informal set of good practice over time. Formalising and modifying this implicit knowledge is challenging, particularly when there is limited documentation (e.g. spreadsheet formulas).
- **Interdisciplinary Communication -** Within multidisciplinary models, each discipline has its own nomenclature which must be communicated to the other disciplines involved. Given the limited documentation in many spreadsheets, this may result in the same figure to be included under different names in different units.
- **Project Adaptation -** In contrast with many fixed purpose models implementing a clear specification (e.g. tax law), most engineering models, whilst trying to be as general as possible, often require some tweaking to fit the exact nature of the task at hand. Due to its scope, an IRM model often requires adaptation to each project for the following reasons:
  - **Models too broad -** A model's data requirements are large and can prove broader than the scope of the project, especially during early design stages. This leads to difficulty in fulfilling all the data requirements.
  - **Models too narrow -** A common cause of model adaptation is to meet project specific concerns. For example the inclusion of irrigation and grey water recycling is critical in water stressed areas but is rarer in more temperate climates and so may need to be added to the model.
  - **Cause and Effect unclear -** Project adaptation for these reasons is a difficult activity - the scale of the model makes identification of cause and effect between an input to be modified and the final sustainability metric difficult to determine, especially because of the interrelated nature of multidisciplinary models.
- **Difficulty of Optimisation -** Once an engineering model is applied to a project the most common use is to create a number of design improvement recommendations. This is difficult since it depends on understanding both the overview and the detail of the model. This requires high levels of implicit knowledge in varying assumptions and understanding the flow of cause and effect across multiple discipline models to identify the handful of most advantageous steps that could be taken to improve the design.
- **Implementation -** Whilst spreadsheet based models are common and support ease of use and modification (a survey undertaken by the authors identified around 1,000 engineering analysis models in use within a large engineering firm). There is a growing body of evidence that spreadsheet models in common with other large software products are likely to contain errors at unacceptable rates. A good summary of the current evidence is available in [Panko, 2008].

In summary, there are clear obstacles in the use of spreadsheet based multidisciplinary engineering models. This paper demonstrates the value of model analysis tools to support practitioners in their information intensive tasks.

3. Methodology

As proposed in [Liang, 2011] with application to the design process, we propose and demonstrate an Extraction and Analysis Methodology (EAM) consisting of a series of techniques to help expose, reduce and manage model complexity. In this paper we explore the impact on multi-disciplinary engineering models. We demonstrate insight into multidisciplinary model composition and show value for designers in quickly focusing efforts into optimisation.

The methodology has the following steps:

1. **Obtain** - Model and project objectives.
2. **Define** - Key Performance Indicators (KPIs) of interest to the project.
3. **Extract** - Slice model to expose and reduce complexity to produce a smaller model computing only the KPIs of interest.
4. **Analyse - Visualise** - Visualise model to aid comprehension and show cause and effect.
5. **Analyse - Metrics** - Compute metrics on calculation model to give insight into model composition.
6. **Optimise** - Set variable ranges to formalise implicit knowledge enabling sensitivity analysis to give insight and focus optimisation effort.

The benefits of this methodology are in the value they provide to the practitioner. Firstly, by reducing the problem size and allowing visualisation to enable interactive exploration of cause and effect. Secondly, by providing metrics and insight into the multidisciplinary composition of the model we show the interaction of various disciplines. Finally, a sensitivity analysis provides further insight and focuses design effort enabling faster optimisation. The methodology also aids model development and evolution as the models are adapted to new projects.

4. Related Work

Studies have identified the presence [Panko, 2008; Clermont, 2005] and frequency [Blayney, 2006] of spreadsheet errors. We know that the majority of modellers do not have formal training in spreadsheet based modelling [Panko, 2008]. A body of literature has developed aiming to formalise a taxonomy of spreadsheet modelling bugs [Panko, 2010]. The risks of these errors are commonly underestimated and few users of spreadsheets consider the risks of such errors [Blayney, 2006]. Indeed very few practitioners consider that they need tools for debugging their models. There have been a number of studies into auditing tools for spreadsheets (e.g. [Blayney, 2006] for tax purposes). Historically there has been much interest in deriving visualisations based on the calculation graph of a spreadsheet [Kankuzi, 2008; Shiozawa, 1999]. Several visualisation tools have been proposed to avoid costly errors.

The novelty of our approach is that rather than treating a spreadsheet as simply a software artefact we consider the insight each step and tool in our methodology can generate for the model maintainer with a view to aiding them as they optimise a design. This is particularly a challenge for engineering models as oppose to financial models which have previously been the focus of research. These engineering models through their constant evolution and adaptation to projects present new research challenges. Particularly we propose a life-cycle methodology for the use of such tools by practitioners. We also consider for the first time, the challenges that a multidisciplinary model brings to the challenge of spreadsheet engineering. For example, considering approaches for assessing multidisciplinary communication within models (Sections 7 and 8). We also consider how sensitivity analysis may be performed in large spreadsheet based models. This is enabled through our extraction and analysis methodology and has the potential to generate substantial insight for practitioners as evidenced in Section 10. Finally, we consider the evolution of complex models as they are developed and applied to projects. As discussed in Section 11 this is a great source of insight into the model and a future research challenge.

5. Model Extraction

The first stage of the methodology is to extract a slice of the model from Excel. Slicing a model or computer program is a well-known technique [Weiser, 1981] that allows consideration of only the portion of the model involved. In this context, slicing extracts only spreadsheet cells involved in the calculation of particular outputs, reducing the model size and complexity.

We recursively extract cells by starting from the outputs of interest (e.g. annual per capita carbon emissions), read their formula parsing them for references to other cells, recursively extracting these until no more cells are referenced. We used a mathematical expression evaluation library NCalc and modified the grammar to be compatible with Microsoft Excel formulas and implemented a subset of Excel functions allowing internal evaluation of formulas to enable validation of analysis. In contrast with many other approaches [Reichwein, 1999; Shiozawa, 1999; Kankuzi, 2008] this formula parsing approach enables us to gain insight within formulas, for example differentiating cells referenced from arithmetic from table lookup functions which reference hundreds of cells. This enables simplification of the extracted model slice and resultant graph of cells. We also extract cell values and names to aid comprehension of visualisations, metrics and sensitivity analysis.

6. Visualisation

Taking inspiration from [Shiozawa99; Kankuzi08], our methodology includes a calculation graph visualisation. We present cells and ranges as nodes in the graph and references between them as edges. We colour the nodes according to which discipline model they originate from, giving insight to discipline communication. Additionally, we support interactive exploration of the calculation graph under several layouts each highlighting different aspects of the graph.

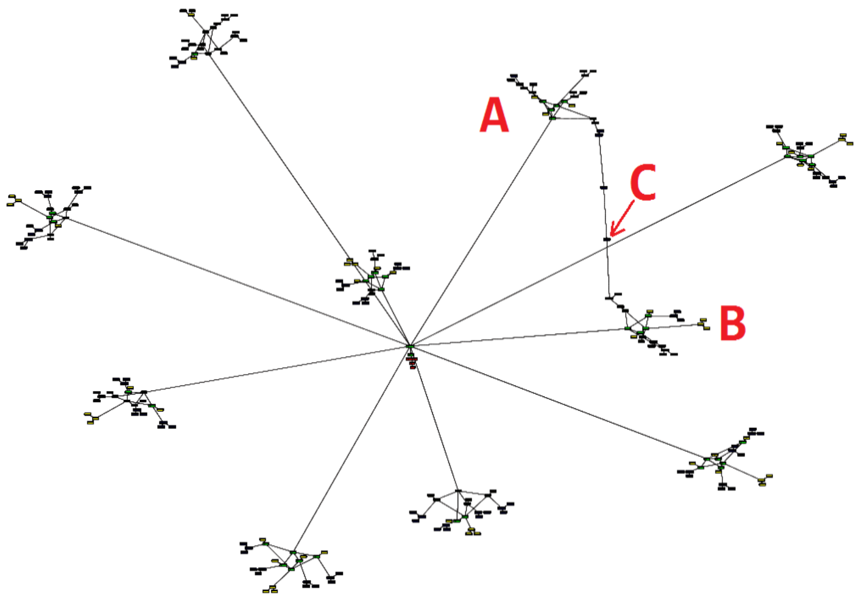

Figure 3 Calculation graph for CO2e emissions percapita per annum for external transport. Layout highlights sub-calculations for ten modes of transportation.

For example Figure 3 highlights the complexity of the CO_2e emissions per capita per annum for external transport calculation within Arup's IRM model. This model slice contains 255 cells and is visualised according to a linlog energy force model which highlights strongly connected sub-graphs. Hence we see ten sub-graphs (calculations) feeding into the metric (the central node in the graph). These correspond to the calculation of carbon emissions for ten modes of transport.

An interesting graph anomaly is that two sub-calculations are connected ("A" and "B"). Upon selecting node "C" linking both calculation clusters ("A" and "B"), a list of the ways this cell is used in the calculation of the metric is generated. Further investigation shows the input value (“C”) to represent the CO_2e emissions for diesel buses per passenger kilometre. This is used in the calculation of both the *bus* and *coach* modes of transport ("A" and "B"). This is unexpected since coaches are normally have around a quarter of the CO_2e emissions of buses. This implies the carbon emissions for coaches could be overestimated in the model. This issue was reported to the IRM engineers who agreed the issue was unexpected and had been fixed in later versions of the model but could have been an assumption carried over from a previous project where coaches and buses have similar CO_2e emissions on small islands.

This demonstrates the utility of slicing and visualisation tools to aid understanding and examination of complex engineering models.

7. Model Metrics

Having extracted a slice of a multidisciplinary engineering model various graph metrics can be automatically calculated to give insight into the multidisciplinary composition of the calculation model.

Firstly we can partition the calculation graph by discipline and gain a measure of their complexity via the cell count and number of inputs in their partition. This is shown in Figure 4 which also shows the average valency (average number of cells each cell references and is referenced by). More references show more complexity and interconnectivity which although harder to maintain, may model reality more accurately. Arup's IRM model’s carbon calculation has 2,357 nodes with average valency of 2.89. In Figure 4 we see the model's focus upon Energy and Passenger Transport with the Transport input models and the Energy output models containing most complexity and interconnectivity.

Discipline Model	Cell Counts	Inputs	% Inputs	Average Valency
Land Use (LU)	38	24	63%	3.24
Socio Economic (SE)	38	23	61%	1.87
Passenger Trans (PT)	210	180	86%	1.57
Pass Trans Coeff (PTCo)	140	99	71%	2.44
Energy Demands (ED)	477	371	78%	1.89
Logistics (Lo)	133	111	83%	1.33
Logistics Coeff (LoCo)	16	16	100%	2.75
Water (Wa)	111	111	100%	1.00
Energy Supply (ES)	34	33	97%	1.79
Energy Sup Coeff (ESCo)	12	12	100%	6.00
Convert Factors (CF)	2	2	100%	18.00
Out: Energy Dem (SSED)	185	12	6%	3.32
Out: Energy Sup (SSES)	244	48	20%	4.40
Out: Logistics (SSLo)	67	0	0%	3.99
Out: Pass Trans (SSPT)	366	0	0%	3.71
Out: Socio-Econ (SSSE)	14	0	0%	4.21
Out: Water (SSW)	264	75	28%	4.08
Project Outputs (Out)	6	0	0%	14.83

Figure 4 Per discipline metrics calculated from a calculation graph extracted from a model slice for annual per capita carbon emissions.

From the number of inputs in each model we gain an indication of each discipline’s data demands. Finally we see that although each discipline has both an input and an output model, this demarcation is not strictly observed in all disciplines. The inputs within output models are of particular concern; though these are sometimes conversion factors or calculation options. Similarly many input models have up to 40% non-input (i.e. calculation) cells. This is acceptable since they summarise the input data for use in other models (e.g. total land use).

Together with metrics for the most referenced input data and sub-calculations, these multidisciplinary metrics give a key overview of the model focus as well as aiding the maintenance of the model by checking whether design rules are followed. This is particularly important in engineering models where model structure is constantly evolved by practitioners.

8. Discipline Coupling

	01LU	02SE	03PT	PTCo	04ED	05Lo	LoCo	Wa	08ES	ESCo	CF	SS_Lo	SS_PT	SS_SE	SS_ES	SS_W	SS_ED	Out
01LU	19	5	0	0	0	0	0	0	0	0	0	0	0	12	0	15	53	0
02SE	0	19	0	0	0	0	0	0	0	0	0	0	0	23	0	5	0	0
03PT	0	0	60	0	0	0	0	0	0	0	0	0	210	0	0	0	0	0
PTCo	0	0	0	81	0	0	0	0	0	0	0	0	180	0	0	0	0	0
04ED	0	0	0	0	424	0	0	0	0	0	0	0	0	0	0	0	53	0
05Lo	0	0	0	0	0	44	0	0	0	0	0	89	0	0	0	0	0	0
LoCo	0	0	0	0	0	0	0	0	0	0	0	44	0	0	0	0	0	0
Wa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	111	0	0
08ES	0	0	0	0	0	0	0	0	1	0	0	0	0	0	59	0	0	0
ESCo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	72	0	0	0
CF	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	35	0	0
SS_Lo	0	0	0	0	0	0	0	0	0	0	0	44	0	0	0	0	45	0
SS_PT	0	0	0	0	0	0	0	0	0	0	0	0	453	0	0	0	60	3
SS_SE	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	7	0	5
SS_ES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	424	0	1	59
SS_W	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	449	6	0
SS_ED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	0	175	12
Out	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5

Figure 5 Discipline coupling matrix shows discipline communication in the IRM model. Matrix should be read ``x values in *row* model are used by *column* model''. Circles indicate the presence of indirect references.

Since multidisciplinary models contain sub-models from many different disciplines, we consider the interconnections between these disciplines as shown by data dependencies in spreadsheet formulas.

As a concrete example, one hypothesis proposed by the IRM engineers was that the transport model was not connected to the land-use model (since it uses software external to the spreadsheet). In order to test this, a discipline coupling matrix was created (Figure 5). This is calculated by considering all edges in the calculation graph and entering them into the matrix according to which disciplines they are from/to (effectively recording cross worksheet reference in formulas). We see the passenger transport and logistics models (PT, Lo and their Coefficients) are indeed not directly connected to the land-use (LU) model, thus confirming the IRM engineers' hypothesis.

Due to the breakdown of inputs/output models within disciplines we see that the top right quadrant covers output models reading from input models. The bottom left quadrant covers input models reading from output models (which shouldn't and doesn’t occur). Much of the model complexity is found in the bottom right quadrant with interconnected calculation models. The diagonal shows sub-model complexity via internal references. We also consider indirect references (reference via another model) and note the primacy of the energy demand and supply models which reference almost all other disciplines.

This is a key technique for considering multidisciplinary engineering models and enables validation that the spreadsheet created matches a conceptual model of communication dataflow.

9. Coupling Metrics

Given the number of sub-models comprising the IRM model, there is much similarity between many large spreadsheets and large software programs. Considering each discipline's models as separate code packages we can apply standard software engineering code metrics [Martin, 2006] to the discipline coupling matrix.

	Afferent Coupling (Responsibility)	Efferent Coupling (Independence)	Instability
Land Use	4	0	0%
Socio Economic	2	1	33%
Passenger Trans	1	0	0%
Pass Trans Coeff	1	0	0%
Energy Demands	1	0	0%
Logistics	1	0	0%
Logistics Coeff	1	0	0%
Water	1	0	0%
Energy Supply	1	0	0%
Energy Sup Coeff	1	0	0%
Convert Factors	2	0	0%
Out: Energy Dem	2	6	75%
Out: Energy Sup	2	3	60%
Out: Logistics	1	3	75%
Out: Pass Trans	2	2	50%
Out: Socio-Econ	2	2	50%
Out: Water	1	5	83%
Project Outputs	0	4	100%

Figure 6 Software engineering metrics normally applied to large software projects [Martin06] are applied to multidisciplinary models to gain insight into model maintainability and stability to change.

We calculate measures of a model's *responsibility to* and *independence from* other models in terms of the data they provide and consume from other models. We use these to compute *instability* to *model change* to identify which models are most likely to cause difficulty for project adaptation.

Firstly, we compute a model's *afferent* coupling [Martin, 2006] by counting the number of discipline models (worksheets) which reference cells in the given model (worksheet). This gives a measure of the responsibility of a model to other models. Models with high *afferent* coupling are less easy to adapt to new projects as changes must avoid breaking its dependant's expectations.

Secondly, we compute *efferent* coupling [Martin06] by counting the number of models (worksheets) which cells in a given model (worksheet) reference. This gives a measure of the independence of the model, with lower scores considered more independent. Models with poor independence are likely to be affected by changes in other models.

Finally we compute a measure of a model's instability to change [Martin, 2006] as follows, where 0% is stable and 100% is unstable.

$$\frac{\text{efferent}}{\text{afferent} + \text{efferent}} = \text{Instability}$$

Figure 6 shows the results for the IRM model. As expected most discipline input models are highly independent and not likely to be affected by changes to other models. Conversely the output models have varying levels of dependence on other models and so have higher levels of instability. This indicates they are more likely to be affected by model changes, particularly as the model evolves. Instability also coarsely identifies flows of effects from changes in input.

These metrics allow engineers to discover how difficult it may be to make changes to a given model and how likely these changes are to affect other disciplines' models; frequent reference to these metrics should create more modular model which are less costly to adapt.

10. Sensitivity Analysis

One common engineering task is to optimise a design for a given KPI, for example annual per capita carbon emissions. This is difficult since the designer must identify all input cells which affect the KPI, consider their ranges and then attempt to find combinations of values which optimise the KPI whilst considering the impacts of doing so.

In support of this we created tools to apply a sensitivity analysis to a slice of the spreadsheet corresponding to all of the cells involved in calculating a KPI of interest. A sensitivity analysis identifies the input factors to which the KPI is most sensitive to changes in. This enables the designer to focus upon the subset of inputs which have the most effect on the KPI, increasing their productivity.

Variable	Normalised Sensitivity for CO_2e Emissions Per Capita: Total	Non-Domestic Buildings	External Transport
FuelType Petrol City Car	100	0	100
CO2 emissions from gas combustion	91	100	0
FuelType Electric Heavy Rail	78	0	78
District Heat Demand - Gas Boiler	71	73	0
District Heat Efficiency - Gas Boiler	71	73	0
Gas Network Efficiency	68	83	0
Gas Network Demand	62	78	0
Electricity Demand from CHP	57	68	0
CH4 emissions from biomass	47	52	0
Efficiency of Heat from biomass	46	55	0

Figure 7 A sensitivity analysis identifies the variable with most scope to impact a KPI. Results normalised to the most impactful variable. We show impact upon total percapita carbon and side effects on some constituent parts of this figure.

In contrast to many tools we use Design of Experiments techniques to create efficient experiments for interrogating the sensitivity of a model. These techniques take a set of factors (inputs), which affect the output of interest, along with the maximum and minimum value each factor can take (set by the practitioner). A series of model runs is then constructed with varying combinations of factors set at their maximum or minimum levels. These are then run and the results analysed. We use a Plackett-Burman (PB) sensitivity analysis [Plackett, 1946] due to its computational efficiency, which comes at the cost of insight only into the effects of factors and not their interactions.

As an example we consider the annual per capita carbon emissions KPI, extract the corresponding model slice and identify its numeric inputs. For each input the maximum and minimum range of the variable is established with engineers from the appropriate discipline. Note that not all numeric inputs are variable e.g. conversion factors. This produced 933 parameters for a sensitivity analysis; Figure 7. shows the results. This requires 2,563 simulation runs, the Excel-Sensitivity tool runs one run per 0.72 seconds on a Quad Core (Intel i7 720QM) machine, running four experiments concurrently.

Since we can test the sensitivity of more than one KPI to the same set of factors at very little extra cost, we explore side effects on the breakdown of the total per capita CO_2e emissions. This gives insight into the relative importance of each sub-metric to the total and what scope there is for affecting each. For example, different fuel type metrics affect the total CO_2e emissions and the transport KPIs but do not affect the non-domestic buildings sub-metric. Interestingly, we see that district heating has a surprisingly high effect on the carbon efficiency, as do Combined Heat and Power (CHP) systems should they be included in the masterplan. These results can be broken down by discipline for more detailed insight.

In conclusion we identify these benefits of a sensitivity analysis on an engineering model:

- **Design Insight** - The designer gains knowledge of the design space, the interactions between the design parameters and the output KPIs of interest allowing a focusing of effort upon only those variables the KPIs is most sensitive to and similarly gaining insight into side effects of changes on other KPIs.
- **Design Space Exploration** - Whilst running the analysis we automatically create and evaluate several thousand designs. Exploration of these allows designers to quickly understand potential configurations and directions for design improvements.
- **Identification of effects of assumptions** - Within most engineering models there are a large number of calculation assumptions. For example, the carbon emissions of buses per passenger kilometre. If included within a sensitivity analysis (the max/min values determining the confidence interval of the assumption) the engineer gains understanding of the relative importance of the assumptions and the respective effects of error margins; enabling focus on refining model uncertainty which will have most impact.

11. IRM Evolution

One interesting use of EAM is its repeated application to a model, particularly as it is adapted to meet the requirements of new projects. We explored the application of the EAM toolkit with three IRM models developed over a number of years from a concept case study to a globally used tool; demonstrating the transferability and scalability of the methodology and tools.

Figure 8 shows such application of EAM to Arup's IRM model. The size of the model has increased dramatically as more detail and accuracy have been added to the model. This is partly due to the most recent IRM model containing data tables localised to geographical regions. The increase in size also reflects an increase in complexity, as noted by the number of Excel functions called within the model. All figures in the table refer to the slice of the model corresponding to annual per capita carbon emissions. The complexity increase compounds the problems discussed in Section 2, highlighting the need for computational support.

Formulas Used in IRM models					
IRM 2008		IRM 2009		IRM 2011	
1,234 Cells 2,360 References		2,357 Cells 3,404 References		37,926 Cells 253,222 References	
SUM	79	SUM	176	IF	5250
		IF	99	MATCH	2714
		TYPE	81	HLOOKUP	2714
				ROUNDUP	1717
				ISERROR	1357
				SUM	1223
				VLOOKUP	198
				SUMIF	78
				AND	57
				ISNUMBER	28
				Misc	7

Figure 8 We applied the EAM [Liang11] toolkit to three different IRM models ranging from a concept model to a fully developed model to a globally used geographically localized tool.

From computing the metrics discussed in Sections 7-9 for each model, we identified the change in focus over time from water modelling through to energy and carbon models by considering the change in complexity and connectivity between the disciplines within the model. These insights demonstrate transferability of the approach. We have been able to apply the process and tools to an Arup vertical transportation model from start to end within one working day reporting valuable insight into the model which was accepted by its expert maintainer.

12. Further Work

Firstly, we see that high data demands are a barrier to IRM adoption. However, it may be possible for automatic or semi-automatic methods to be applied to the calculation graph to attempt to produce an abstracted version of the model with fewer data requirements. Methods such as sensitivity analysis could be used to identify parts of the model for removal which have limited impact upon the accuracy of the overall model results.

Secondly, whilst a PB sensitivity analysis gives good insight into the model, other forms of sensitivity analysis might be applied (dependent upon their tractability). One of the more interesting methods would be to apply automatic differentiation tools to the overall model formula allowing accurate insight into the multi-variate sensitivities of the model.

Finally, given the formalisation of discipline specific implicit knowledge behind the variable ranges for a sensitivity analysis, it would be interesting to use these as the constraints to an optimisation engine performing constraint based optimisation upon the model. Of course such optimisation would never replace an engineer's insight into which combinations of variable values are practicable but could serve as a valuable decision support tool within IRM models and other engineering models.

13. Conclusions

The case study presented demonstrates the need and the value of computational tools in understanding complex multidisciplinary models. The techniques explored aid practitioners in model comprehension, optimisation and evolution; as evidenced by exploring Arup's IRM model as a representative model and the aid given to practitioners. Many of whom have no formal programming experience with model development tasks. Model slicing allows reduction of model complexity to show only the salient points. Interactive exploration of the model as a calculation graph valuably enables users to build a mental model of how the calculation works. Model metrics are an interesting and valuable way of gaining detailed insight into the model and its composition. Metrics pertaining to the multidisciplinary nature of the model give higher level insight into interdisciplinary communication. Finally, sensitivity analysis is a valuable technique for understanding the relative importance of hundreds of input variables when seeking to optimise for a given KPI or checking model assumptions. Repeated application of EAM to a model clearly identifies changes in model composition and focus. EAM and its techniques can be applied more widely than IRM models and have been applied to other confidential engineering models.

In conclusion:

- We present a methodology and tool suite for systematic, automatic analysis of large spreadsheet-based models with novel metrics to assess internal communication and integrated sensitivity analysis to aid practitioners in optimisation.
- We applied this methodology with a focus upon multidisciplinary engineering assessment models, a model type not widely studied within literature.
- We demonstrated the methodology's application through practical case studies with an industrial multidisciplinary sustainability model, identifying insight for practitioners and model evolution over three generations.

The authors would like to gratefully acknowledge the support of the EPSRC and Arup in funding this work.

14. References

Ayaz, E. and Levitas, J. (2008), "Spatially Linked Integrated Resource Management (IRM): A Tool to Inform Eco-city Planning", Proceedings of the 8th International Eco-city Conference (Eco-city 2012).

Blayney, P. J. (2006), "An Investigation of the Incidence and Effect of Spreadsheet Errors Caused by the Hard Coding of Input Data Values into Formulas".

Clermont, M. (2005), "Heuristics for the Automatic Identification of Irregularities in Spreadsheets", SIGSOFT Software. Eng. Notes.

Kankuzi, B. and Ayalew, Y. (2008), "An End-user Oriented Graph-based Visualization for Spreadsheets", Proceedings of the 4th International Workshop on End-user Software Engineering.

Kepran, H. (2002), "Creating a Framework for Integrated Resource Management" ICLEI 2002.

Liang, H. and Birch, D. (2011), "Extraction and Analysis Methodology for Supporting Complex Sustainable Design", Proceedings of the18th International Conference on Engineering Design (ICED11).

Martin, R. and Martin, M. (2006), "Agile Principles, Patterns, and Practices in C#", Prentice Hall.

Page, J., Grange, N. and Kirkpatrick, N. (2008), "The Integrated Resource Management (IRM) Model Guidance Tool for Sustainable Urban Design", Proceedings of the 25th Conference on Passive and Low Energy Architecture (PLEA08).

Panko, R. R. (2008), (Revised edition) (2008), "What We Know About Spreadsheet Errors", Journal of End User Computing, pages 15–21.

Panko, R. R. and Aurigemma, S. (2010), "Revising the Panko-Halverson Taxonomy of Spreadsheet Errors Decision". Support Sys, pages 235-244.

Plackett, R.L and Burman, J.P. (1946), "The Design of Optimum Multifactorial Experiments", Biometrika, pages 305-325.

Reichwein, J., Rothermel, G. and Burnett, M. M. (1999), "Slicing Spreadsheets: An Integrated Methodology for Spreadsheet Testing and Debugging", Proceedings of the 2nd Conference on Domain-specific Languages.

Shiozawa, H., Okada, K. and Matsushita, Y. (1999), "3D Interactive Visualization for Inter-Cell Dependencies of Spreadsheets", IEEE Symposium on Information Visualization.

Weiser, M. (1981), "Program Slicing", Proceedings of the 5th International Conference on Software Engineering.